MECHANICAL ENGINEERING

(CONVENTIONAL AND OBJECTIVE TYPE)

[For the Students of U.P.S.C (Engg. Services); I.A.S. (Engg. Group); B.S.c. Engg.; Diploma and Other Competitive Courses]

R. S. KHURMI

J.K. GUPTA

PREFACE TO THE SEVENTH EDITION

We feel satisfied in presenting the new edition of this treatise. The favourable and warm reception, which the previous edition of this book has enjoyed all over India and abroad, is a matter of great satisfaction for us.

The new edition of this treatise has been thoroughly revised and brought up-to-date. The mistakes which had crept in, have been eliminated. A new chapter on '*Automobile Engineering*' has been added. To make this treatise more useful for the students preparing for various competitive examinations, theory has been added before dealing with the objective type questions which have been divided into the following four groups :

1. Multiple Choice Questions ; 2. True and False Questions; 3. Fill in the Blanks; and 4. Matching Type Questions.

More than one thousand Objective Type Questions from various examining bodies have been added. The solutions of Important Objective Type Question have been added at the end of this treatise

We wish to express our sincere thanks to numerous professors and students, both at home and abroad, for sending their valuable suggestions and recommending the book to their students and friends. We hope, that they will continue to patronise this book in the future also.

Any errors, omissions and mistakes, for the improvement of this volume brought to our notice, will be thankfully acknowledged and rectified in the next edition.

R.S. KHURMI
J.K. GUPTA

PREFACE TO THE FIRST EDITION

We take an opportunity to present this treatise entitled as *Mechanical Engineering (Objective Type)* to the students preparing for Degree, Diploma and other competitive examinations. The object of this book is to present the subject with multiple choice questions and answers.

While writing the book, we have constantly kept in mind the latest examination requirements of the students preparing for U.P.S.C. (Indian Engg. Services) and I.A.S. (Engg. Group) examinations. No effort has been spared to enrich the book with objective type questions of different types. The answers to these questions have been provided at the end of each chapter. In short, it is hoped that the book will embrace the requirements of all the engineering students and will earn appreciation of all the fellow teachers.

Although every care has been taken to check the mistakes and misprints, yet it is difficult to claim perfection. Any errors, omissions and suggestions for the improvement of this treatise, brought to our notice, will be thankfully acknowledged and incorporated in the next edition.

R.S. KHURMI
J.K. GUPTA

CONTENTS

1

Engineering Mechanics

1.1 Introduction

The Engineering Mechanics is that branch of Engineering-science which deals with the principles of mechanics along with their applications to engineering problems. It is sub-divided into the following two main groups:

(*a*) Statics, and (*b*) Dynamics

The *Statics* is that branch of Engineering Mechanics which deals with the forces and their effects, while acting upon the bodies at rest.

The *Dynamics* is that branch of Engineering Mechanics which deals with the forces and their effects, while acting upon the bodies in motion. It is further sub-divided into the following two branches:

(*i*) Kinetics, and (*ii*) Kinematics

The *Kinetics* is that branch of Dynamics, which deals with the bodies in motion due to the application of forces.

The *Kinematics* is that branch of Dynamics which deals with the bodies in motion without taking into account the forces which are responsible for the motion.

1.2 Force

It may be defined as an agent which produces or tends to produce, destroy or tends to destroy the motion of a body. A force while acting on a body may

(*a*) change the motion of a body,

(*b*) retard the motion of a body,

(*c*) balance the forces already acting on a body, and

(*d*) give rise to the internal stresses in a body.

In order to determine the effects of a force acting on a body, we must know the following characteristics of a force:

(*i*) The magnitude of the force,

(*ii*) The line of action of the force,

(*iii*) The nature of the force, *i.e.* push or pull, and

(*iv*) The point at which the force is acting.

In M. K. S. system of units, the magnitude of the force is expressed in kilogram-force (briefly written as kgf) and in S.I. system of units, the force is expressed in newtons (briefly written as N). It may noted that

$$1 \text{ kgf} = 9.81 \text{ N}$$

1.3 Resultant Force

It is a single force which produces the same effect as produced by all the given forces acting on a body. The resultant force may be determined by the following three laws of forces :

1. *Parallelogram law of forces.* It states that if two forces, acting simultaneously on a particle, be represented in magnitude and direction by the two adjacent sides of a parallelogram, then their resultant may be represented in magnitude and direction by the diagonal of a parallelogram which passes through their points of intersection.

For example, let us consider two forces P and Q acting at angle θ at point O as shown in Fig. 1.1. The resultant is given by,

$$R = \sqrt{P^2 + Q^2 + 2PQ\cos\theta}$$

If the resultant (R) makes an angle α with the force P, then

$$\tan\alpha = \frac{Q\sin\theta}{P + Q\cos\theta}$$

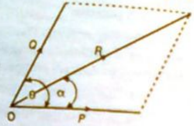


Fig. 1.1

2. *Triangle law of forces.* It states that if two forces, acting simultaneously on a particle, be represented in magnitude and direction by the two sides of a triangle taken in order, then their resultant may be represented in magnitude and direction by the third side of the triangle taken in opposite order.

3. *Polygon law of forces.* It states that if a number of forces, acting simultaneously on a particle, be represented in magnitude and direction by sides of a polygon taken in order, then their resultant is represented in magnitude and direction by the closing side of the polygon taken in opposite order.

Notes : 1. The resultant of more than two intersecting forces may be found out by resolving all the forces horizontally and vertically. In such cases, resultant of the forces is given by

$$R = \sqrt{(\Sigma H)^2 + (\Sigma V)^2}$$

where ΣH = Sum of resolved parts in the horizontal direction, and

ΣV = Sum of resolved parts in the vertical direction.

If the resultant (R) makes an angle α with the horizontal, then

$$\tan\alpha = \Sigma V / \Sigma H$$

2. If the resultant of a number of forces, acting on a particle, is zero then the particle will be in equilibrium. Such a set of forces, whose resultant is zero, are known as *equilibrium forces*. The force, which brings the set of forces in equilibrium is called an *equilibriant*. It is equal to the resultant force in magnitude but opposite in direction.

3. A number of forces acting on a particle will be in equilibrium when $\Sigma H = 0$ and $\Sigma V = 0$.

1.4 System of Forces

When two or more than two forces act on a body, they are said to form a *system of forces*. Following are the various system of forces:

1. *Coplaner forces.* The forces, whose lines of action lie on the same plane are known as coplaner forces.

2. *Concurrent forces.* The forces, which meet at one point, are known as concurrent forces.

3. *Coplaner concurrent forces.* The forces, which meet at one point and their lines of action also lie on the same plane, are called coplaner concurrent forces.

4. *Coplaner non-concurrent forces.* The forces, which do not meet at one point but their lines action lie on the same plane, are known as coplaner non-concurrent forces.

5. *Non-coplaner concurrent forces.* The forces, which meet at one point but their lines of action do not lie on the same plane are known as non-coplaner concurrent forces.

6. *Non- coplaner non-concurrent forces.* The forces, which do not meet at one point and their lines of actions do not lie on the same plane are called non-coplaner non-concurrent forces.

1.5 Lami's Theorem

It states that if three coplaner forces acting at a point be in equilibrium, then each force is proportional to the sine of the angle between the other two forces. Mathematically

$$\frac{P}{\sin\alpha} = \frac{Q}{\sin\beta} = \frac{R}{\sin\gamma}$$

where P, Q and R are the three forces and α, β and γ are the angles as shown in Fig 1.2.

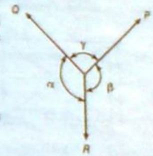


Fig. 1.2

1.6 Moment of a Force

It is the turning effect produced by a force, on the body, on which it acts. The moment of a force is equal to the product of the force and the perpendicular distance of the point, about which the moment is required and the line of action of the force. Mathematically, the moment of a force P about point O as shown in Fig 1.3,

$$= P \times l$$

The unit of moment depends upon the units of force and perpendicular distance. If the force is in newtons and the perpendicular distance in metres, then the unit of moment will be newton-metre (briefly written as N-m).

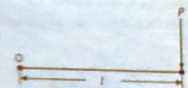


Fig. 1.3

1.7 Varignon's Principle of Moments (or Law of Moments)

It states that if a number of coplaner forces acting on a particle are in equilibrium, then the algebraic sum of their moments about any point is equal to the moment of their resultant force about the same point.

1.8 Parallel Forces

The forces, whose lines of action are parallel to each other, are said to be *parallel forces*. If the parallel forces act in the same direction then these are known as *like parallel forces*. When the parallel forces act in opposite directions, then these are known as *unlike parallel forces*.

1.9 Couple

The two equal and opposite forces, whose lines of action are different, form a couple, as shown in Fig. 1.4.

The perpendicular distance (x) between the lines of action of two equal and opposite forces is known as arm of the couple. The magnitude of the couple (*i.e.* moment of a couple) is the product of one of the forces and the arm of the couple. Mathematically,

$$\text{Moment of a couple} = P \times x$$

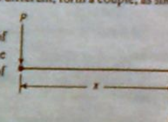


Fig. 1.4

A little consideration will show, that a couple does not produce any translatory motion (*i.e.* motion in a straight line), but a couple produces a motion of rotation of the body on which it acts.

1.10 Centre of Gravity

The point through which the whole mass of the body acts, irrespective of the position of the body, is known as *centre of gravity* (briefly written as c.g.) The plane geometrical figures (like rectangle, triangle, circle etc.) have only areas but no mass. The centre of area of such figures is known as *centroid* or *centre of gravity* of the area of the body. It may be noted that every body has one, and only one, centre of gravity. The centre of gravity of some simple figures is given below.

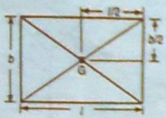


Fig. 1.5

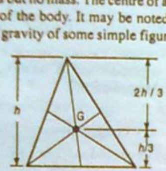


Fig. 1.6

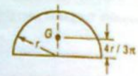


Fig. 1.7

1. The centre of gravity of a uniform rod is at its middle point.

2. The centre of gravity (G) of a rectangle (or parallelogram) lies at a point where its diagonals intersect, as shown in Fig. 1.5.

3. The centre of gravity (G) of a triangle lies at a point where the three medians of the triangle intersect, as shown in Fig. 1.6.

Note : A median is a line joining the vertex and the middle point of the opposite side.

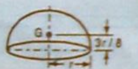


Fig. 1.8

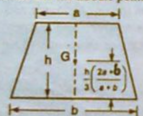


Fig. 1.9

Fig. 1.10

4. The centre of gravity of a semi-circle lies at a distance of $4r/3\pi$ from its base measured along the vertical radius, as shown in Fig. 1.7.

5. The centre of gravity of a hemisphere lies at a distance of $3r/8$ from its base, measured along the vertical radius, as shown in Fig. 1.8.

6. The centre of gravity of a trapezium with parallel sides a and b, lies at a distance of $\frac{h}{3}\left(\frac{2a+b}{a+b}\right)$ measured from side b, as shown in Fig. 1.9.

7. The centre of gravity of a right circular solid cone lies at a distance of $h/4$ from its base, measured along the vertical axis, as shown in Fig. 1.10.

1.11 Moment of Inertia

It may be defined as the moment of the moment *i.e.* second moment of mass or area of a body. It is usually denoted by I.

Consider a body of total mass m. Let it is composed of small particles of masses m_1, m_2, m_3 ......etc. If k_1, k_2, k_3......etc. are the distances from a fixed line, as shown in Fig. 1.11, then mass moment of intertia of the whole body is given by

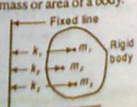


Fig. 1.11

$$I = m_1(k_1)^2 + m_2(k_2)^2 + m_3(k_3)^2 + \ldots\ldots$$
$$= m.k^2$$

If, instead of mass, the area of the figure is taken into consideration, then moment of inertia of the area is given by

$$I = a_1(k_1)^2 + a_2(k_2)^2 + a_3(k_3)^2 + \ldots\ldots$$

where k is called the *radius of gyration*. It is defined as *the distance from a given reference where the whole mass or area of the body is assumed to be concentrated to give the same value of I.*

In S.I. units, the unit of mass moment of inertia is kg-m^2 and the moment of intertia of the area is expressed in m^4 or mm^4.

If the moment of inertia of a body about an axis passing through its centre of gravity (*i.e.* I_G) is known, then the moment of inertia about any other parallel axis (*i.e.* I_P) may be obtained by using parallel axis theorem.

According to parallel axis theorem, the moment of inertia about a parallel axis,

$$I_P = I_G + m.h^2 \quad \text{...(considering mass of the body)}$$
$$= I_G + a.h^2 \quad \text{...(considering area of the body)}$$

where h = Distance between two parallel axes.

The following are the values of I for simple cases :

1. The moment of inertia of a thin disc of mass m and radius r, about an axis passing through its centre of gravity and perpendicular to the plane of the disc is

$$I_G = m.r^2/2 = 0.5\,mr^2$$

and moment of inertia about a diameter,

$$I_D = m.r^2/4 = 0.25\,mr^2$$

2. The moment of inertia of a thin rod of mass m and length l, about an axis passing through its centre of gravity and perpendicular to its length is

$$I_G = m.l^2/12$$

and moment of inertia about a parallel axis through one end of the rod,

$$I_P = m.l^2/3$$

3. The moment of inertia of a rectangular section having width b and depth d as shown in Fig. 1.12, is given by

$$I_{XX} = \frac{bd^3}{12}\ ; \text{ and}$$

$$I_{YY} = \frac{db^3}{12}$$

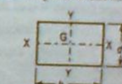


Fig. 1.12

4. The moment of inertia of a hollow rectangular section, as shown in Fig. 1.13, is given by

$$I_{XX} = \frac{BD^3}{12} - \frac{bd^3}{12}\ ; \text{ and}$$

$$I_{YY} = \frac{DB^3}{12} - \frac{db^3}{12}$$

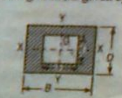


Fig. 1.13

5. The moment of inertia of a circular section of diameter D as shown in Fig. 1.14, is given by

$$I_{XX} = I_{YY} = \frac{\pi D^4}{64}$$

Fig. 1.14

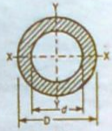


Fig. 1.15

6. The moment of inertia of a hollow circular section of outer diameter D and inner diameter d, as shown in Fig. 1.15, is given by

$$I_{XX} = I_{YY} = \frac{\pi}{64}\left[D^4 - d^4\right]$$

7. The moment of inertia of a triangular section of height h, about an axis passing through its centre of gravity G and parallel to the base BC, as shown in Fig. 1.16, is given by

$$I_G = \frac{bh^3}{36}$$

and moment of inertia about the base BC,

$$I_{BC} = \frac{bh^3}{12}$$

Fig. 1.16

1.12 Friction

A force acting in the opposite direction to the motion of the body is called *force of friction* or simply *friction*. It is of the following two types :

1. Static friction ; and 2. Dynamic friction.

The friction, experienced by a body, when at rest, is known as *static friction*.

The friction experienced by a body, when in motion, is called *dynamic friction*. It is also called *kinetic friction*. It is of the following two types:

(*a*) Sliding friction ; and (*b*) Rolling friction.

The friction, experienced by a body, when it slides over another body, is known as *sliding friction*.

The friction experienced by a body, when balls or rollers are interposed between the two surfaces, is known as *rolling friction*.

1.13 Limiting Friction

The maximum value of frictional force, which comes into play, when a body just begins to slide over the surface of the other body, is known as *limiting friction*.

1.14 Laws of Static Friction

Following are the laws of static friction :

1. The force of friction always acts in a direction, opposite to that in which the body tends to move.

2. The magnitude of force of friction is exactly equal to the force, which tends the body to move.

3. The magnitude of the limiting friction bears a constant ratio to the normal reaction between the two surfaces.

4. The force of friction is independent of the area of contact between the two surfaces.

5. The force of friction depends upon the roughness of the surfaces.

1.15 Laws of Dynamic or Kinetic Friction

Following are the laws of dynamic or kinetic friction :

1. The force of friction always acts in a direction, opposite to that in which the body tends to move.

2. The magnitude of the kinetic friction bears a constant ratio to the normal reaction between the two surfaces.

3. For moderate speeds, the force of friction remains constant. But it decreases slightly with the increase of speed.

1.16 Coefficient of Friction

It is defined as the ratio of limiting friction (F) to the normal reaction (R_N) between the two bodies. It is generally denoted by μ. Mathematically,

$$\text{Coefficient of friction, } \mu = \frac{F}{R_N}$$

1.17 Limiting Angle of Friction

It is defined as the angle which the resultant reaction (R) makes with the normal reaction (R_N).

Consider a body A of weight W resting on a horizontal plane B as shown in Fig. 1.17. If a horizontal force P is applied to the body, no relative motion takes place until the applied force P is equal to the force of friction F, acting opposite to the direction of motion. The magnitude of this force of friction is $F = \mu W = \mu . R_N$, where R_N is the normal reaction.

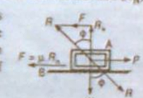


Fig. 1.17

In the limiting case, when the body just begins to move, it is in equilibrium under the action of the following three forces :

1. Weight of the body (W),
2. Applied horizontal force (P), and
3. Reaction (R) between the body A and the plane B.

The reaction R must, therefore, be equal and opposite to the resultant of W and P and will be inclined at an angle ϕ to the normal reaction (R_N). This angle ϕ is called the *limiting angle of friction* or simply *angle of friction*. From Fig. 1.17, we find that

$$\tan\phi = \frac{F}{R_N} = \frac{\mu . R_N}{R_N} = \mu$$

1.18 Angle of Repose

It is the angle of inclination (α) of the plane to the horizonal, at which the body just begins to move down the plane. A little consideration will show that the body will begin to move down the plane, if the angle of inclination (α) of the plane is equal to the angle of friction (ϕ). From Fig. 1.18, we find that

$$W \sin \alpha = F = \mu . R_N = \mu . W \cos \alpha$$

or

$$\tan \alpha = \mu = \tan \phi$$

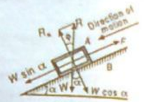


Fig. 1.18

1.19 Minimum Force Required to Slide a Body on a Rough Horizontal Plane

Let a body A of weight W is resting on a rough horizontal plane B, as shown in Fig. 1.19. Let an effort P is applied at an angle θ to the horizontal, such that the body just begins to move. From Fig. 1.19, we find that

$$P \cos \theta = F = \mu . R_N = \mu (W - P \sin \theta)$$

$$= \tan \phi (W - P \sin \theta) \quad ...(\because \mu = \tan \phi)$$

$$= \frac{\sin \phi (W - P \sin \theta)}{\cos \phi}$$

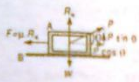


Fig. 1.19

$$P \cos \theta \cos \phi + P \sin \theta \sin \phi = W \sin \phi$$

$$\therefore \quad P = \frac{W \sin \phi}{\cos (\theta - \phi)}$$

For P to be minimum, $\cos (\theta - \phi)$ should be maximum, *i.e.*

$$\cos (\theta - \phi) = 1 \quad \text{or} \quad \theta - \phi = 0 \quad \text{or} \quad \theta = \phi$$

In other words, the effort P is minimum when its inclination (θ) with the horizontal is equal to the angle of friction (ϕ).

$$\therefore \quad P_{min} = W \sin \theta$$

1.20 Effort Required to Move the Body Up an Inclined Plane

The effort (P) required to move the body up an inclined plane as shown in Fig. 1.20, is given by

$$P = \frac{W \sin (\alpha + \phi)}{\sin [\theta - (\alpha + \phi)]}$$

where

W = Weight of the body,

α = Angle of inclination of the plane with the horizontal,

θ = Angle which the line of action of P makes with the weight of the body W, and

ϕ = Angle of friction.

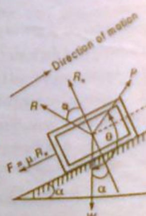


Fig. 1.20

Notes : 1. When friction is neglected, then $\phi = 0$. In that case,

$$P_o = \frac{W \sin \alpha}{\sin (\theta - \alpha)}$$

2. When effort P is applied horizontally, then $\theta = 90°$. In that case

$$P = \frac{W \sin (\alpha + \phi)}{\cos (\alpha + \phi)} = W \tan (\alpha + \phi)$$

3. When effort P is applied parallel to the plane, then $\theta = 90° + \alpha$. In that case,

$$P = \frac{W \sin (\alpha + \phi)}{\cos \phi} = W (\sin \alpha + \mu \cos \alpha)$$

1.21 Effort Required to Move the Body Down an Inclined Plane

The effort (P) required to Move the body down an inclined plane as shown in Fig. 1.21, is given by

$$P = \frac{W \sin (\alpha - \phi)}{\sin [\theta - (\alpha - \phi)]}$$

Notes: 1. When friction is neglected, then $\phi = 0$. In that case,

$$P_o = \frac{W \sin (\alpha)}{\sin (\theta - \alpha)}$$

2. When effort is applied horizontally, then $\theta = 90°$. In that case

$$P = \frac{W \sin (\alpha - \phi)}{\cos (\alpha - \phi)} = W \tan (\alpha - \phi)$$

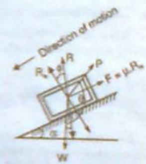


Fig. 1.21

3. When effort is applied parallel to the plane, then $\theta = 90° + \alpha$. In that case,

$$P = \frac{W \sin (\alpha - \phi)}{\cos \phi} = W (\sin \alpha - \mu \cos \alpha)$$

1.22 Efficiency of an Inclined Plane

It is defined as the ratio of the effort required neglecting friction (*i.e.* P_o) to the effort required considering friction (*i.e.* P). Mathematically, efficiency of an inclined plane,

$$\eta = P_o / P$$

1.23 Screw Jack

The principle, on which a screw jack works is similar to that of an inclined plane. If one complete turn of a screw thread is imagined to be unwound, from the body of the screw jack and developed, it will form an inclined plane, as shown in Fig. 1.22.

From the geometry of the figure,

$$\tan \alpha = \frac{p}{\pi d}$$

where

α = Helix angle,

p = Pitch of thread, and

d = Mean diameter of the screw.


Fig. 1.22

In a screw jack, the effort (P) required at the circumference of screw is same as discussed for inclined plane, *i.e.*

For raising the load, $P = W \tan (\alpha + \phi)$

and for lowering the load, $P = W \tan (\alpha - \phi)$

Notes: 1. When friction is neglected, then $\phi = 0$. In that case

$$P_0 = W \tan \alpha$$

2. The efficiency of a screw jack is given by

$$\eta = \frac{P_0}{P} = \frac{W \tan \alpha}{W \tan(\alpha + \phi)} = \frac{\tan \alpha}{\tan(\alpha + \phi)}$$

3. The efficiency of a screw jack is maximum, when helix angle,

$$\alpha = 45° - \phi / 2$$

and the maximum efficiency is given by

$$\eta_{max} = \frac{1 - \sin \phi}{1 + \sin \phi}$$

1.24 Lifting Machine

It is a device, which enables us to lift a heavy load W, by a comparatively small effort P. The following terms are commonly used in lifting machines :

1. *Mechanical advantage (M.A.).* It is the ratio of load lifted (W) to the effort applied (P).

2. *Velocity ratio (V.R.).* It is the ratio of the distance moved by the effort (y) to the distance moved by the load (x).

3. *Input of the machine.* It is the workdone on the machine. It is equal to the product of effort and the distance through which it moves (*i.e.* $P \times y$).

4. *Output of the machine.* It is the workdone by the machine. It is equal to the product of load lifted and the distance through which it has been lifted (*i.e.* $W \times x$).

5. *Efficiency of the machine.* It is ratio of output to the input of the machine. Mathematically, efficiency of the machine,

$$\eta = \frac{\text{Output}}{\text{Input}} = \frac{\text{Workdone by the machine}}{\text{Workdone on the machine}} = \frac{W \times x}{P \times y} = \frac{W}{P} \times \frac{1}{y/x} = \frac{M.A.}{V.R.}$$

6. *Ideal machine.* If the efficiency of the machine is 100 %, *i.e.* if output is equal to input, then the machine is said to be a perfect or ideal machine.

7. *Reversible machine.* If a machine is capable of doing some work in the reversed direction, after the effort is removed, then the machine is known as reversible machine. The condition for a machine to be reversible is that its efficiency should be more than 50 %.

8. *Non- reversible or self locking machine.* If a machine is not capable of doing some work in the reversed direction, after the effort is removed, then the machine is known as non-reversible or self locking machine. The condition for a machine to be non-reversible or self locking is that its efficiency should be less than 50 %.

9. *Law of the machine.* It is the relationship between the load lifted (W) and the effort applied (P). It is given by the equation,

$$P = m.W + C$$

where m = A constant (called coefficient of friction) which is equal to the slope of the line AB as shown in Fig. 1.23, and

C = Another constant, which represents the machine friction.

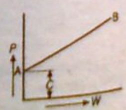


Fig. 1.23

10. *Maximum mechanical advantage.* The maximum mechanical advantage of a lifting machine is given by

$$\text{Max. } M.A. = 1/m$$

11. *Maximum efficiency.* The maximum efficiency of a lifting machine is given by

$$\text{Max. } \eta = \frac{1}{m \times V.R.}$$

1.25 Systems of Pulleys

The following three systems of pulleys are commonly used :

1. *First system of pulleys.* For such a system, velocity ratio, $(V.R.) = 2^n$

where n = Number of pulleys

2. *Second system of pulleys.* For this system, velocity ratio, $(V.R.) = n$

3. *Third system of pulleys.* For such a system, velocity ratio, $(V.R.) = 2^n - 1$

1.26 Frame

A frame may be defined as a structure made up of several bars, riveted or welded together. These are made up of angle irons or channel sections and are called members of the frame or framed structure. The frames may be classified into the following two groups:

1. Perfect frame, and 2. Imperfect frame.

A *perfect frame* is that which is composed of members just sufficient to keep it in equlibrium, when loaded, without any change in its shape. A perfect frame should satisfy the following expression:

$$n = 2j - 3$$

where n = Number of members, and

j = Number of joints.

An *imperfect frame* is one which does not satisfy the above equation ($n = 2j - 3$). The imperfect frame which has number of members (n) less than $2j - 3$, is known as *deficient frame*. If the number of members are greater than $2j - 3$, then the imperfect frame is known *redundant frame*.

1.27 Speed

It is the rate of change of displacement with respect to its surrounding. Since the speed of a body is irrespective of its direction, therefore it is a scalar quantity.

1.28 Velocity

It is also the rate of change of displacement with respect to its surrounding, in a particular direction. Since the velocity is always expressed in a particular direction, therefore it is a vector quantity.

1.29 Acceleration

It is the rate of change of velocity of a body. It is said to be positive, when the velocity of a body increases with time and it is negative when the velocity decreases with time. The negative acceleration is also called *retardation*.

1.30 Equations of Linear Motion

The following are the equations of linear motion :

1. $v = u + a.t$

2. $s = u.t + \frac{1}{2} a.t^2$

3. $v^2 = u^2 + 2\,a.s$, and

4. $s = \frac{(u + v)\,t}{2}$

where
u = Initial velocity,
v = Final velocity,
a = Acceleration, and
s = Displacement of the body in time t seconds.

Notes: 1. The above equations apply for uniform acceleration.

2. In case of vertical motion, the body is subjected to gravity. Thus the acceleration due to gravity (g) should be substituted in place of a, in the above equations.

3. The value of g is taken as + 9.81 m / s² for downward motion, and — 9.81 m / s² for upward motion.

4. When a body falls from a height h, its velocity v with which it will hit the ground, is given by

$$v = \sqrt{2g\,h}$$

1.31 Newton's Laws of Motion

Following are the Newton's three laws of motion:

1. *Newton's first law of motion.* It states that *everybody continues in the state of rest or of uniform motion, in a straight line, unless it is acted upon by some external force.*

2. *Newton's second law of motion.* It states that *the rate of change of momentum is directly propotional to the impressed force, and takes place in the same direction, in which the force acts.*

3. *Newton's third law of motion.* It states that *to every action, there is always an equal and opposite reaction.*

1.32 Mass, Weight and Momentum

The *mass* is a matter contained in a body. It is expressed in kilogram (kg).

The *weight* of a body is a force by which it is attracted towards the centre of the earth. It is expressed in newtons (N). The relation between the mass and weight of a body is given by

$$W = m.g$$

The *momentum* is defined as the total motion possessed by a body. Mathematically,

Momentum = Mass × Velocity

According to Newton's second law of motion, the applied force or impressed force (P) is directly propotional to rate of change of momentum. Thus

$$P \propto m\left(\frac{v-u}{t}\right) \quad \text{or} \quad P \propto m.a \quad \text{or} \quad P = k.m.a$$

where k is a constant of proportionality.

For the sake of convenience, the unit of force adopted is such that it produces unit acceleration (*i.e.* 1 m / s²) to a body of unit mass (*i.e.* 1 kg).

$$\therefore \quad P = m.a = \text{Mass} \times \text{Accelration}$$

In S.I system of units, the unit of force is newton (briefly written as N). A newton may be defined as the force, while acting upon a body of mass 1 kg, produces an acceleration of 1 m / s² in the direction of which it acts. Thus

$$1\,\text{N} = 1\,\text{kg} \times 1\,\text{m/s}^2 = 1\,\text{kg-m/s}^2$$

Note: A force equal in magnitude but opposite in direction and collinear with the applied force or impressed force producing the acceleration, is known as *inertia force*. Mathematically, inertia force,

$$F_1 = -\,m.a$$

1.33 D-Alembert's Principle

Consider a rigid body acted upon by a system of forces. The system may be reduced to a single resultant force (P) acting on the body whose magnitude is given by the product of the mass of the body (m) and the linear acceleration (a) of the centre of mass of the body. According to Newton's second law of motion,

$$P = m.a \quad \text{or} \quad P - m.a = 0 \quad \text{or} \quad P + F_1 = 0$$

Thus D-Alembert's principle states that, *the resultant force acting on the body together with the reversed effective force or inertia force are in equilibrium.*

1.34 Motion of a Lift

Consider a lift (elevator or cage) carrying some mass and moving with uniform acceleration.

Let
m = Mass carried by the lift in newtons,
a = Uniform acceleration of the lift in m/s², and
R = Reaction of the lift or tension in the cable supporting the lift in newtons.

When the lift is moving upwards as shown in Fig. 1.24 (*a*), then

$$R - m.g = m.a \quad \text{or} \quad R = m.g + m.a = m(g + a)$$

When the lift is moving downwards as shown in Fig. 1.24 (*b*), then

$$m.g - R = m.a \quad \text{or} \quad R = m.g - m.a = m(g - a)$$

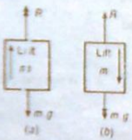


Fig. 1.24

1.35 Motion of Two Bodies Connected by a String

Consider a light inextensible string passing over a smooth pulley, as shown in Fig. 1.25, so that the tension (T) in both the strings is same. Let mass m_1 is greater than mass m_2. Since the string is inextensible, the upward acceleration of mass m_2 will be equal to the downward acceleration of mass m_1. This acceleration is given by

$$a = \frac{g\,(m_1 - m_2)}{m_1 + m_2}\ \text{m/s}^2$$

and tension in the string,

$$T = \frac{2m_1.m_2.g}{m_1 + m_2}\ \text{N}$$

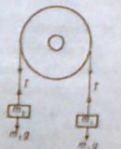


Fig. 1.25

Let us now consider the following cases of motion of two bodies connected by a string.

1. First of all, let us consider the motion of two bodies connected by an inextensible string, one of which is hanging freely and the other is lying on a smooth horizontal plane as shown in Fig. 1.26. Since the string is inextensible, the tension (T) in both the strings will be equal. The acceleration of the system is given by

$$a = \frac{m_1.g}{m_1 + m_2}\ \text{m/s}^2$$

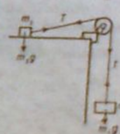


Fig. 1.26

and $$T = m_2 . a = \frac{m_1 . m_2 . g}{m_1 + m_2} \text{ N}$$

2. If instead of smooth plane, it is a rough horizontal plane, as shown in Fig. 1.27, then frictional force equal to $\mu . R_N = \mu . m_2 . g$ will act in the opposite direction to the motion of mass m_2, where μ is the coefficient of friction. In such a case,

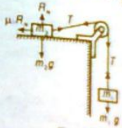


Fig. 1.27

$$a = \frac{g\,(m_1 - \mu . m_2)}{m_1 + m_2} \text{ m/s}^2$$

and $$T = \frac{m_1 . m_2 . g\,(1 + \mu)}{m_1 + m_2} \text{ N}$$

3. When the plane is a smooth inclined plane, as shown in Fig. 1.28, then

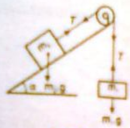


Fig. 1.28

$$a = \frac{g\,(m_1 - m_2 \sin \alpha)}{m_1 + m_2} \text{ m/s}^2$$

and $$T = \frac{m_1 . m_2 . g\,(1 + \sin \alpha)}{m_1 + m_2} \text{ N}$$

4. When the plane is a rough inclined plane, as shown in Fig. 1.29, then

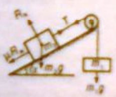


Fig. 1.29

$$a = \frac{g\,(m_1 - m_2 \sin \alpha - \mu . m_2 \cos \alpha)}{m_1 + m_2} \text{ m/s}^2$$

and $$T = \frac{m_1 . m_2 . g\,(1 + \sin \alpha + \mu \cos \alpha)}{m_1 + m_2} \text{ N}$$

1.36 Projectile

A particle moving under the combined effect of vertical and horizontal forces, is called a *projectile*. The following terms are commonly used in projectiles:

1. *Trajectory*. It is the path traced by a projectile in the space.
2. *Velocity of projection*. It is the velocity with which a projectile is projected.
3. *Angle of projection*. It is the angle, with the horizontal, at which the projectile is projected.
4. *Time of flight*. It is the total time taken by a projectile, to reach maximum height and to return back to the ground.
5. *Range*. It is the distance between the point of projection and the point where the projectile strikes the ground.

1.37 Equation of the Path of a Projectile

Let O = Point of projection,

u = Velocity of projection, and

α = Angle of projection with the horizontal.

Consider a point P as the position of particle, after time t seconds with x and y as co-ordinates, as shown in Fig. 1.30.

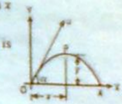


Fig. 1.30

The equation of the path of a projectile or the equation of trajectory is given by

$$y = x \tan \alpha - \frac{g\,x^2}{2u^2 \cos^2 \alpha}$$

Since this is the equation of a parabola, therefore the path traced by a projectile is a porabola. The following are the important equations used in projectiles:

1. The time of flight (t) of a projectile on a horizontal plane is given by

$$t = \frac{2u \sin \alpha}{g}$$

2. The horizontal range (R) of a projectile is given by

$$R = \frac{u^2 \sin 2\alpha}{g}$$

For a given velocity of projectile, the range will be maximum when $\sin 2\alpha = 1$ or $\alpha = 45°$.

3. The maximum height (H) of a projectile on a horizontal plane is given by

$$H = \frac{u^2 \sin^2 \alpha}{2g}$$

4. The time of flight of a projectile when it is projected from O on an upward inclined plane as shown in Fig. 1.31, is given by

$$t = \frac{2u \sin (\alpha - \beta)}{g \cos \beta}$$

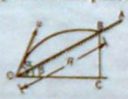


Fig. 1.31

where β is the inclination of plane OA with the horizontal.

When the projectile is projected on a downward inclined plane, then

$$t = \frac{2u \sin (\alpha + \beta)}{g \cos \beta}$$

5. The range of projectile when it is projected from O to B on an upward inclined plane, as shown in Fig. 1.31, is given by

$$R = OB = \frac{2u^2 \sin (\alpha - \beta) \cos \alpha}{g \cos^2 \beta} = \frac{u^2}{g \cos^2 \beta} [\sin (2\alpha - \beta) - \sin \beta]$$

For a given velocity of projectile, the range will be maximum when,

$$\alpha = 45° + \frac{\beta}{2} = \frac{\pi}{4} + \frac{\beta}{2}$$

When the projectile is projected on a downward inclined plane, then

$$R = \frac{2u^2 \sin (\alpha + \beta) \cos \alpha}{g \cos^2 \beta}$$

1.38 Angular Displacement

It is the angle described by a particle from one point to another, with respect to time. Since the angular displacement has both magnitude and direction, therefore it is a vector quantity.

In order to completely represent an angular displacement by a vector, it must fix the following three conditions :

1. Direction of the axis of rotation,
2. Magnitude of angular displacement, and
3. Sense of the angular displacement.

1.39 Angular Velocity

It is the rate of change of angular displacement of a body. It is usually expressed in revolutions per minute (r.p.m.) or radians per second (rad / s). It is denoted by a Greek letter ω (omega). Since it has magnitude and direction, therefore it is a vector quantity.

If a body is rotating at N r.p.m, then corresponding angular velocity,

$$\omega = \frac{2\pi N}{60} \text{ rad / s}$$

Note: If the body is rotating at ω rad / s along a circular path of radius r, then its linear velocity (v) is given by

$$v = \omega . r$$

1.40 Angular Acceleration

It is the rate of change of angular velocity. It is usually expressed in rad / s^2 and is denoted by a Greek letter α (alpha). It is also a vector quantity.

Notes : 1. If the body is moving along a circular path of radius r and with angular acceleration α, then its linear acceleration is given by

$$a = \alpha \times r$$

2. When a body moves along a circular path, its linear acceleration will have two components; one is the normal component and other is tangential component. The normal component of the acceleration is known as *normal or centripetal acceleration* (a_r). Its value is given by

$$a_r = \frac{v^2}{r} = \omega^2 . r$$

3. When the body moves along a circular path with uniform velocity, then there will be no tangential acceleration, but it will have only centripetal acceleration.

4. When the body moves along a straight path, then there will be no centripetal acceleration, but it will have only tangential acceleration, in the same direction as its velocity and displacement.

1.41 Simple Harmonic Motion

A body is said to move or vibrate with simple harmonic motion (briefly written as S.H.M.), if it satisfies the following two conditions:

1. Its acceleration is always directed towards the centre known as point of reference or mean position, and
2. Its acceleration is proportional to the distance from that point.

The following terms are commonly used in simple harmonic motion :

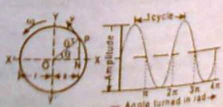


Fig. 1.32

1. *Amplitude.* It is the maximum displacement of a body from its mean position. In Fig. 1.32, OX and OX' is the amplitude of particle P. The amplitude is always equal to the radius of the circle.

2. *Periodic time.* It is the time taken for one complete revolution of the particle. Mathematically,

$$\text{Periodic time, } t_p = \frac{2\pi}{\omega} \text{ seconds}$$

3. *Frequency.* It is the number of cycles per second and it is the reciprocal of time period (t_p). Mathematically,

$$\text{Frequency} \quad n = \frac{1}{t_p} = \frac{\omega}{2\pi} \text{ Hz}$$

Note : In S.I. units, the unit of frequency is hertz (briefly written as Hz) which is equal to one cycle per second.

1.42 Velocity and Acceleration of a Particle Moving with Simple Harmonic Motion

Consider a particle, moving round the circumference of a circle of radius r, with a uniform angular velocity ω rad / s, as shown in Fig. 1.32. Let P be any position of the particle after t seconds and θ be the angle turned by the particle in t seconds. We know that

$$\theta = \omega . t, \text{ and } \quad x = r\cos\theta = r\cos\omega t$$

The velocity of N (which is the projection of P on XX') is the component of the velocity of P parallel to XX'.

$$\therefore \quad v_N = v\sin\theta = \omega . r\sin\theta$$

$$= \omega\sqrt{r^2 - x^2} \qquad \ldots (\because r\sin\theta = NP = \sqrt{r^2 - x^2})$$

The velocity is maximum, when $x = 0$, *i.e.* when N passes through O (*i.e.* mean position).

$$v_{max} = \omega . r$$

The acceleration of N is the component of the acceleration of P parallel to XX' and is directed towards the centre O.

$$\therefore \quad a_N = \omega^2 . r\cos\theta = \omega^2 . x$$

The acceleration is maximum, when $x = r$, *i.e.* when P is at X or X'.

$$\therefore \quad a_{max} = \omega^2 . r$$

1.43 Simple Pendulum

A simple pendulum, in its simplest form, consists of a heavy bob suspended at the end of a light inextensible and flexible string as shown in Fig. 1.33. The other end of the string is fixed at O. When the bob is at A, it is in equilibrium or mean position. It may be noted that, when the angle θ (through which the string is displaced) is less than 4°, then the bob will oscillate between B and C with simple harmonic motion.

For a simple pendulum, periodic time,

$$t_p = 2\pi\sqrt{\frac{L}{g}}$$

and frequency of oscillation,

$$n = \frac{1}{t_p} = \frac{1}{2\pi}\sqrt{\frac{g}{L}}$$

Fig. 1.33

Notes : 1. The motion of the bob from one extremity to the other (*i.e.* from B to C or C to B) is known as *beat* or *swing*. Thus one beat = 1/2 oscillation, and periodic time for one beat,

$$t_p = \pi\sqrt{\frac{L}{g}}$$

2. A pendulum, which executes one beat per second (*i.e.* one complete oscillation in two seconds) is known as *second's pendulum*.

1.44 Closely Coiled Helical Spring

Consider a closely coiled helical spring whose one end is fixed and the other end carries a load $W = m.g$, as shown in Fig. 1.34. Let AA be the equlibrium position of the spring after the load is attached. If the spring is streched upto BB' and then released, the load will move up and down with simple harmonic motion.

Fig. 1.34

For a closely coiled helical spring, periodic time,

$$= 2\pi\sqrt{\frac{m}{s}} = 2\pi\sqrt{\frac{\delta}{g}}\ \text{second} \qquad \left(\because \delta = \frac{m.g}{s}\right)$$

and frequency of oscillation,

$$n = \frac{1}{t_p} = \frac{1}{2\pi}\sqrt{\frac{s}{m}} = \frac{1}{2\pi}\sqrt{\frac{g}{\delta}}\ \text{Hz}$$

where s = Stiffness of the spring, and

δ = Deflection of the spring.

If the mass of the spring (m_1) is also taken into consideration, then frequency of oscillation,

$$n = \frac{1}{2\pi}\sqrt{\frac{s}{m + \frac{m_1}{3}}}$$

1.45 Compound Pendulum

When a rigid body is suspended vertically and it oscillates with a small amplitude under the action of force of gravity, the body is known as compound pendulum, as shown in Fig. 1.35.

For a compound pendulum, the periodic time is given by

$$t_p = 2\pi\sqrt{\frac{(k_G)^2 + h^2}{g.h}}$$

Fig. 1.35

and frequency of oscillation,

$$n = \frac{1}{t_p} = \frac{1}{2\pi}\sqrt{\frac{g.h}{(k_G)^2 + h^2}}$$

where k_G = Radius of gyration about an axis through the centre of gravity G and perpendicular to the plane of motion, and

h = Distance of point of suspension O from the centre of gravity G.

Notes : 1. The equivalent length of a simple pendulum (L) which gives the same frequency as that of compound pendulum is given by

$$L = \frac{(k_G)^2 + h^2}{h}$$

2. The periodic time of compound pendulum is minimum when the distance between the point of suspension and the centre of gravity (*i.e.* h) is equal to the radius of gyration of the body about its centre of gravity (*i.e.* k_G).

$\therefore$ Minimum periodic time of a compound pendulum,

$$t_{p\,(min)} = 2\pi\sqrt{\frac{2k_G}{g}}$$

1.46 Centre of Percussion

Sometimes, the centre of oscillation is termed as *centre of percussion*. It is defined as that point at which a blow may be struck on a suspended body so that the reaction at the support is zero. It may be noted that

1. The centre of percussion (C) is below the centre of gravity (G), as shown in Fig. 1.36, and at a distance of

$$l = \frac{(k_G)^2}{h}$$

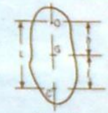


Fig. 1.36

2. The distance between the centre of suspension (O) and the centre of percussion (C) is equal to the equivalent length of simple pendulum, *i.e.*

$$L = l + h$$

3. The centre of suspension (O) and the centre of percussion (C) are inter-changeable.

1.47 Torsional Pendulum

It is used to find the moment of inertia of a body experimentally. The body (say a disc or flywheel) whose moment of intertia is to be determined is suspended by three long flexible wires A, B and C as shown in Fig. 1.37. When the body is twisted about its axis through a small angle θ and then released, it will oscillate with simple harmonic motion.

For a torsional pendulum, the periodic time is given by

$$t_p = \frac{2\pi k}{r}\sqrt{\frac{l}{g}}$$

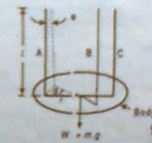


Fig. 1.37

and frequency of oscillation,

$$n = \frac{1}{t_p} = \frac{r}{2\pi k}\sqrt{\frac{g}{l}}$$

where r = Distance of each wire from the axis of the body,

k = Radius of gyration, and

l = Length of each wire.

1.48 Centripetal and Centrifugal Force

When a body of mass m kg is moving with angular velocity ω rad/s, in a circular path of radius r, then centripetal force,

$$F_c = m.\omega^2.r$$

This force acts radially inwards and is essential for circular motion. According to Newton's third law of motion, the body must exert a force radially outwards of equal magnitude. This force is known as centrifugal force, whose magnitude is given by

$$F_c = m.\omega^2.r$$

1.49 Superelevation

Whenever a roadway (or railway) is laid on a curved path, then its outer edge is always made higher than the inner edge, to keep the vehicle in equilibrium while in motion. The amount by which the outer edge is raised, is known as *cant* or *superelevation*. In case of roadways, the process of providing superelevation is known as banking of the road. The general practice, to define the superelevation in roadways, is to mention the angle of inclination (also called angle of banking) of the road surface, such that

$$\tan\theta = \frac{v^2}{g.r}$$

where v = Velocity of the vehicle, and

r = Radius of circular path.

In case of railways, the general practice to define the superelevation, is to mention the difference of levels between the two rails. In such a case, superelevation is given by

$$S = \frac{G.v^2}{g.r}$$

where G = Gauge of the track.

Notes : 1. When a vehicle is moving on a level circular path, then the maximum velocity of the vehicle, in order to avoid overturning is given by

$$v_{max} = \sqrt{\frac{g.r.a}{h}}$$

and in order to avoid skidding

$$v_{max} = \sqrt{\mu.g.r}$$

where h = Height of C.G. of the vehicle from the ground level,

$2a$ = Distance between the outer and inner wheel, and

μ = Coefficient of friction between the wheels of the vehicle and the ground.

2. When a vehicle moves on a level circular path, the reaction at the inner wheel

$$= \frac{m.g}{2}\left(1 - \frac{v^2.h}{g.r.a}\right)$$

and reaction at the outer wheel

$$= \frac{m.g}{2}\left(1 + \frac{v^2.h}{g.r.a}\right)$$

where m = Mass of the vehicle in kg.

1.50 Collision of Two Bodies

Consider the impact between two bodies which move with different velocities along the same straight line. It is assumed that the point of impact lies on the line joining the centres of gravity of the two bodies. The behaviour of these colliding bodies during the complete period of impact will depend upon the properties of the materials of which they are made. The material of the two bodies may be perfectly elastic or perfectly inelastic.

The bodies which rebound after impact are called *elastic bodies* and the bodies which does not rebound at all after its impact are called *inelastic bodies*. The impact between two lead spheres or two clay spheres is approximately an inelastic impact.

The loss of kinetic energy (E_L) during impact of inelastic bodies is given by

$$E_L = \frac{m_1.m_2}{2(m_1+m_2)}(u_1-u_2)^2$$

where m_1 = Mass of the first body,

m_2 = Mass of the second body,

u_1 and u_2 = Velocities of the first and second bodies respectively.

The loss of kinetic energy (E_L) during impact of elastic bodies is given by

$$E_L = \frac{m_1.m_2}{2(m_1+m_2)}(u_1-u_2)^2(1-e^2)$$

where e = Coefficient of restitution

$$= \frac{\text{Relative velocity after impact}}{\text{Relative velocity before impact}} = \frac{v_2-v_1}{u_1-u_2}$$

Notes : 1. The relative velocity of two bodies after impact is always less than the relative velocity before impact.

2. The value of $e = 0$, for perfectly inelastic bodies and $e = 1$, for perfectly elastic bodies. In case the bodies are neither perfectly inelastic nor perfectly elastic, then the value of e lies between zero and one.

1.51 Work

Whenever a force (F) acts on a body and the body undergoes a displacement (x) in the direction of the force, then the work is said to be done. Mathematically,

$$\text{Workdone} = F \times x$$

If the force varies from 0 to a maximum value of F, then

$$\text{Work done} = \frac{0+F}{2} \times x = \frac{F}{2} \times x$$

The unit of work depends upon the unit of force and the displacement. In S.I. system of units, the practical unit of work is N-m. It is the work done by a force of 1 newton when it displaces a body through 1 metre. The work of 1 N-m is known as joule (briefly written as J), such that 1 N-m = 1 J.

Note : If a couple or torque (T) acting on a body causes the angular displacement (θ) about an axis perpendicular to the plane of the couple, then,

$$\text{Workdone} = T.\theta$$

1.52 Power

It is the rate of doing work or workdone per unit time. In S.I. system of units, the unit of power is watt (briefly written as W) which is equal to 1N-m/s or 1J/s. Generally a bigger unit of power called kilowatt (briefly written as kW) is used which is equal to 1000 W.

Note : If T is the torque transmitted in N-m or J and ω is the angular speed in rad / s, then

$$\text{Power} = T.\omega = T \times \frac{2\pi N}{60} \text{ watts}$$

where N = Speed in r.p.m.

1.53 Energy

It is the capacity of doing work. The mechanical energy is equal to the workdone on a body in altering either its position or its velocity. Following are the three types of mechanical energies :

1. *Potential energy.* It is the energy possessed by a body for doing work, by virtue of its position.

Let m = Mass of the body,

W = Weight of the body = $m.g$, and

h = Distance through which the body falls.

$\therefore$ Potential energy $= W.h = m.g.h$

2. *Strain energy.* It is the potential energy stored by an elastic body when deformed. A compressed spring posseses this type of energy, because it can do some work in recovering its original shape. Thus if a compressed spring of stiffness s newton per unit extension or compression, is deformed through a distance x by a load W, then

$$\text{Strain energy} = \text{Workdone} = \frac{1}{2} W \times x = \frac{1}{2} s.x^2 \qquad ...(\because W = s \times x)$$

3. *Kinetic energy.* It is the energy possessed by a body, for doing work, by virtue of its mass (m) and velocity of motion (v). Mathematically, kinetic energy of the body or kinetic energy of translation,

$$= \frac{1}{2} m.v^2$$

Notes: 1. When a body of mass moment of inertia (I) about a given axis is rotated about that axis with an angular velocity ω, then it possesses some kinetic energy. In this case,

$$\text{Kinetic energy of rotation} = \frac{1}{2} I.\omega^2$$

2. When the body has both linear and angular motions *e.g.* in the locomotive driving wheels and wheels of a moving car, then total kinetic energy of the body

$$= \frac{1}{2} m.v^2 + \frac{1}{2} I.\omega^2$$

OBJECTIVE TYPE QUESTIONS

1. The term 'force' may be defined as an agent which produces or tends to produce, destroys or tends to destroy motion.
   (a) Agree (b) Disagree
2. A force while acting on a body may
   (a) change its motion (b) balance the forces, already acting on it
   (c) give rise to the internal stresses in it (d) all of these
3. In order to determine the effects of a force, acting on a body, we must know
   (a) magnitude of the force (b) line of action of the force
   (c) nature of the force *i.e.* whether the force is push or pull
   (d) all of the above

4. The unit of force in S.I. system of units is
   (a) dyne (b) kilogram (c) newton (d) watt
5. One kg force is equal to
   (a) 7.8 N (b) 8.9 N (c) 9.8 N (d) 12 N
6. A resultant force is a single force which produces the same effect as produced by all the given forces acting on a body.
   (a) True (b) False
7. The process of finding out the resultant force is called .... of forces.
   (a) composition (b) resolution
8. The algebraic sum of the resolved parts of a number of forces in a given direction is equal to the resolved part of their resultant in the same direction. This is known as
   (a) principle of independence of forces (b) principle of resolution of forces
   (c) principle of transmissibility of forces (d) none of these
9. Vectors method for the resultant force is also called polygon law of forces.
   (a) Correct (b) Incorrect
10. The resultant of two forces P and Q acting at an angle θ is
    (a) $\sqrt{P^2 + Q^2 + 2PQ\sin\theta}$ (b) $\sqrt{P^2 + Q^2 + 2PQ\cos\theta}$
    (c) $\sqrt{P^2 + Q^2 - 2PQ\cos\theta}$ (d) $\sqrt{P^2 + Q^2 - 2PQ\tan\theta}$
11. If the resultant of two forces P and Q acting at an angle θ, makes an angle α with the force P, then
    (a) $\tan\alpha = \dfrac{P\sin\theta}{P + Q\cos\theta}$ (b) $\tan\alpha = \dfrac{P\cos\theta}{P + Q\cos\theta}$
    (c) $\tan\alpha = \dfrac{Q\sin\theta}{P + Q\cos\theta}$ (d) $\tan\alpha = \dfrac{Q\cos\theta}{P + Q\sin\theta}$
12. The resultant of two forces P and Q (such that $P > Q$) acting along the same straight line, but in opposite direction, is given by
    (a) $P + Q$ (b) $P - Q$ (c) P/Q (d) Q/P
13. The resultant two equal forces P making an angle θ, is given by
    (a) $2P\sin\theta/2$ (b) $2P\cos\theta/2$ (c) $2P\tan\theta/2$ (d) $2P\cot\theta/2$
14. The resultant of two forces each equal to P and acting at right angles is
    (a) $P/\sqrt{2}$ (b) $P/2$ (c) $P/2\sqrt{2}$ (d) $\sqrt{2}P$
15. The angle between two forces when the resultant is maximum and minimum respectively are
    (a) 0° and 180° (b) 180° and 0° (c) 90° and 180° (d) 90° and 0°
16. If the resultant of the two forces has the same magnitude as either of the forces, then the angle between the two forces is
    (a) 30° (b) 60° (c) 90° (d) 120°

2

Strength of Materials

2.1 Introduction

The strength of materials may broadly be defined as that branch of Engineering - science, which deals with the ability of various types of materials to resist its failure and their behaviour under the action of the forces.

2.2 Stress

When some external system of forces or loads act on a body, the internal forces (equal and opposite) are set up at various sections of the body, which resist the external forces. This internal force per unit area at any section of the body is known as *unit stress* or simply *stress*. Mathematically,

$$\text{Stress, } \sigma = P/A$$

where
P = Force or load acting on the body, and
A = Cross-sectional area of the body.

In S.I. units, the stress is usually expressed in Pascal (Pa) such that $1\text{ Pa} = 1\text{N/m}^2$. In actual practice, we use bigger unit of stress *i.e.*, megapascal (MPa) and gigapascal (GPa) such that

$$1\text{ MPa} = 1 \times 10^6\text{ N/m}^2 = 1\text{N/mm}^2$$
$$1\text{ GPa} = 1 \times 10^9\text{ N/m}^2 = 1\text{kN/mm}^2$$

2.3 Strain

When a system of forces act on a body, it undergoes some deformation. This deformation per unit length is known as *unit strain* or simply a *strain*. Mathematically,

$$\text{Strain, } \varepsilon = \delta l / l$$

where
δl = Change in length of the body, and
l = Original length of the body.

2.4 Tensile Stress and Strain

When a body is subjected to two equal and opposite axial pulls, as a result of which the body tends to extend its length, the stress and strain induced is known as *tensile stress* and *tensile strain*.

2.5 Compressive Stress and Strain

When a body is subjected to two equal and opposite axial pushes, as a result of which the body tends to decrease its length, the stress and strain induced is known as *compressive stress* and *compressive strain*.

2.6 Young's Modulus or Modulus of Elasticity

Hooke's law states that when a material is loaded within elastic limit, the stress is directly proportional to strain, *i.e.*

$$\sigma \propto \varepsilon \quad \text{or} \quad \sigma = E.\varepsilon \quad \text{or} \quad E = \frac{\sigma}{\varepsilon} = \frac{P \times l}{A \times \delta l}$$

where E is a constant of proportionality and is known as *Young's Modulus* or *Modulus of elasticity*.

2.7 Shear Stress and Strain

When a body is subjected to two equal and opposite forces, acting tangentially across the resisting section, as a result of which the body tends to shear off the section, then the stress induced is called *shear stress*. The corresponding strain is known as *shear strain* and it is measured by the angular deformation accompanying the shear stress.

2.8 Shear Modulus or Modulus of Rigidity

It has been found experimentally that within elastic limit, the shear stress is directly proportional to shear strain. Mathematically,

$$\tau \propto \phi \quad \text{or} \quad \tau = C.\phi \quad \text{or} \quad \tau/\phi = C$$

where τ = Shear stress ; ϕ = Shear strain, and C = Constant of proportionality, known as *Shear modulus* or *modulus of rigidity*. It is also denoted by N or G.

2.9 Stress in a Bar due to its own Weight

Consider a bar of length (l) and diameter (d) rigidly fixed at the upper end and hanging freely as shown in Fig. 2.1. The stress at any section in a bar due to its own weight is directly proportional to the distance from the free end. Therefore, stress at a distance x from the free end

$$= Wx$$

and total elongation of the bar,

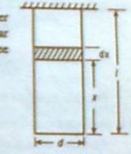


Fig. 2.1

$$\delta l = Wl^2/2E$$

where W = Weight per unit volume of the bar.

Note : When a conical bar of length (l) and base diameter (d) is rigidly fixed with its base diameter at the upper end and is hanging freely, then the total elongation of the bar due to its own weight is given by

$$\delta l = \frac{Wl^2}{6E}$$

2.10 Stresses in Bars of Varying Sections

When a bar is made up of different lengths having different cross-sectional areas, and is subjected to an axial force P, as shown in Fig 2.2, then the total deformation of the bar,

$$\delta l = \delta l_1 + \delta l_2 + \delta l_3 + \ldots$$
$$= \frac{Pl_1}{A_1.E} + \frac{Pl_2}{A_2.E} + \frac{Pl_3}{A_3.E} + \ldots\ldots$$
$$= \frac{P}{E}\left(\frac{l_1}{A_1} + \frac{l_2}{A_2} + \frac{l_3}{A_3} + \ldots\ldots\right)$$

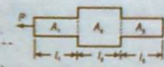


Fig. 2.2

2.11 Stresses in Bars of Uniformly Tapering Circular Section

When a bar of uniformly tapering circular sections is subjected to an axial force P, as shown in Fig. 2.3, then the elongation of the bar,

$$\delta l = \frac{4Pl}{\pi E d_1 d_2}$$

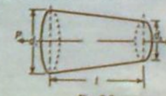


Fig. 2.3

2.12 Stresses in Composite Bars

A composite bar may be defined as a bar made up of two or more different materials, joined together in such a manner, that the system extends or contracts as one unit, equally, when subjected to tension or compression.

Consider a composite bar made up of two different materials as shown in Fig. 2.4.

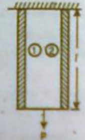


Fig. 2.4

Load shared by bar 1, $P_1 = P \times \dfrac{A_1.E_1}{A_1.E_1 + A_2.E_2}$

and load shared by bar 2, $P_2 = P \times \dfrac{A_2.E_2}{A_1.E_1 + A_2.E_2}$

Since the elongation for both the bars in same (*i.e.* $\delta l_1 = \delta l_2$), therefore

$$\frac{P_1 l}{A_1.E_1} = \frac{P_2 l}{A_2.E_2} \quad \text{or} \quad \frac{\sigma_1}{E_1} = \frac{\sigma_2}{E_2}$$

$$\therefore \quad \sigma_1 = \frac{E_1}{E_2} \times \sigma_2; \text{ and } \quad \sigma_2 = \frac{E_2}{E_1} \times \sigma_1$$

The ratio E_1 / E_2 is known as *modular ratio* of the two materials.

2.13 Stresses due to Change in Temperature — Thermal Stresses

Whenever there is some increase or decrease in the temperature of a body, it causes the body to expand or contract. A little consideration will show that if the body is allowed to expand or contract freely, with the rise or fall of the temperature, no stresses are induced in the body. But, if the deformation of the body is prevented, some stresses are induced in the body. Such stresses are known as *thermal stresses* or *temperature stresses* and the corresponding strains are called *thermal strains* or *temperature strains*.

When a bar of length (l) is subjected to an increase in temperature (t), then the increase in length when the bar is free to expand is given by

$$\delta l = l.\alpha.t$$

where α = Coefficient of linear expansion.

If the ends of the bar are fixed to rigid supports so that its expansion is prevented, then compressive thermal strain induced in the bar,

$$\varepsilon = \delta l / l = l.\alpha.t / l = \alpha.t$$

and thermal stress $= \varepsilon.E = \alpha.t.E$

Note: If the supports yield by an amount equal to δ, then the actual expansion that has taken place is given by

$$\delta l = l.\alpha.t - \delta$$

2.14 Thermal Stresses in Bars of Tapering Section

When a circular bar of uniformly tapering section fixed at its ends is subjected to an increase in temperature (t) as shown in Fig. 2.5, then thermal stress induced

$$= \frac{\alpha.t.E.d_1}{d_2}$$

Fig. 2.5

2.15 Primary or Linear Strain

The deformation of the bar, per unit length in the direction of the force (*i.e.* $\delta l / l$) is known as *primary* or *linear strain*.

2.16 Secondary or Lateral Strain

Every direct stress is always accompanied by a strain in its own direction, and an opposite kind of strain in every direction, at right angles to it. Such a strain is known as *secondary* or *lateral strain*.

2.17 Poisson's Ratio

The ratio of lateral strain to linear strain is called Poisson's ratio.

2.18 Volumetric Strain

The ratio of change in volume to the original volume is known as volumetric strain.

The volumetric strain of a rectangular bar of length (l), breadth (b) and thickness (t) and subjected to an axial force (P) is given by

$$\frac{\delta V}{V} = \frac{P}{b.t.E}\left(1 - \frac{2}{m}\right) = \varepsilon\left(1 - \frac{2}{m}\right)$$

2.19 Bulk Modulus

When a body is subjected to three mutually perpendicular stresses, of equal intensity, the ratio of direct stress to the corresponding volumetric strain is known as *bulk modulus*. It is usually denoted by K.

When a cube is subjected to three mutually perpendicular tensile stresses of equal intensity (σ), then the volumetric strain,

$$\frac{\delta V}{V} = \frac{3\sigma}{E}\left(1 - \frac{2}{m}\right)$$

The relation between bulk modulus and Young's modulus is given by

$$K = \frac{m.E}{3(m-2)}$$

The relation between modulus of elasticity (E) and modulus of rigidity (C) is given by

$$C = \frac{m.E}{2(m+1)}$$

and the relation between E, C and K is given by

$$E = \frac{9KC}{3K + C}$$

2.20 Bearing Stress or Crushing Stress

A localised compressive stress at the surface of contact between two members that are relatively at rest is known as *bearing stress* or *crushing stress*. The bearing stress is taken into account in riveted joints, cotter joints, knuckle joints etc. Let us consider a riveted joint as shown in Fig. 2.6. In such a case, the bearing or crushing stress (*i.e.* the stress at the surface of contact between the rivet and the plate),

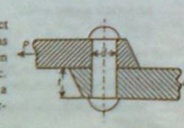


Fig. 2.6

$$\sigma_b \text{ (or } \sigma_c) = \frac{P}{d\,t\,n}$$

where d = Diameter of the rivet,

t = Thickness of the plate,

$d\,t$ = Projected area of the rivet, and

n = Number of rivets per pitch length in bearing or crushing.

2.21 Principal Stresses and Strains

It has been observed that at any point in a strained material, there are three planes, mutually perpendicular to each other, which carry direct stresses only, and no shear stresses. A little consideration will show that out of these three direct stresses, one will be maximum, the other minimum and the third an intermediate between the two. These particular planes, which have no shear stress, are known as *principal planes*. The magnitude of direct stress, across a principal plane, is known as *principal stress*.

2.22 Stress on an Oblique Section of a Body Subjected to Direct Stresses in One Plane

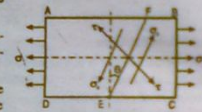


Fig. 2.7

Consider a rectangular body $ABCD$ of uniform cross-sectional area (A) and unit thickness subjected to principal tensile stress σ as shown in Fig. 2.7.

On a section EF, which is inclined at an angle θ to the normal cross-section, the normal and tangential stress will be induced. The normal stress across the section EF is given by

$$\sigma_n = \frac{\text{Force normal to the section } EF}{\text{Area of section } EF}$$

$$= \frac{\sigma A \cos\theta}{A \sec\theta} = \sigma \cos^2\theta \qquad \text{...(i)}$$

and tangential stress (*i.e.* shear stress) across the section EF,

$$\tau = \frac{\text{Force along the section } EF}{\text{Area of section } EF} = \frac{\sigma A \sin\theta}{A \sec\theta} = \sigma \sin\theta.\cos\theta$$

$$= \frac{\sigma}{2} \times 2\sin\theta\cos\theta = \frac{\sigma}{2} \times \sin 2\theta \qquad \text{... (ii)}$$

From equation (*i*), we see that the normal stress across the section EF will be maximum, when $\cos^2\theta = 1$ or $\cos\theta = 1$ or $\theta = 0°$. In other words, the normal cross-section will carry the maximum direct stress.

∴ Maximum normal stress,

$$\sigma_n = \sigma \cos 0° = \sigma$$

From equation (*ii*), we see that the tangential or shear stress across the section EF will be *maximum*, when $\sin 2\theta = 1$ or $2\theta = 90°$ or $270°$ or $\theta = 45°$ or $135°$. In other words, the shear stress will be maximum on two planes inclined at 45° and 135° to the normal section.

∴ Maximum tangential or shear stress,

$$\tau_{max} = \frac{\sigma}{2} \sin 90° = \sigma/2$$

From above, we see that the maximum tangential or shear stress is *one-half* the maximum normal stress.

The resultant stress is given by

$$\sigma_R = \sqrt{(\sigma_n)^2 + (\tau)^2}$$

Note : The above relations hold good for compressive stress also.

2.23 Stresses on an Oblique Section of a Body Subjected to Direct Stresses in Two Mutually Perpendicular Directions

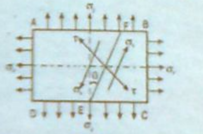


Fig. 2.8

When a body of uniform cross-sectional area and unit thickness is subjected to mutually perpendicular principal tensile stresses σ_x and σ_y as shown in Fig. 2.8, then the normal stress across the section EF is given by

$$\sigma_n = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2} \cos 2\theta \qquad \text{...(i)}$$

Tangential stress (*i.e.* shear stress) across the section EF,

$$\tau = (\sigma_x - \sigma_y)\sin\theta\cos\theta = \frac{\sigma_x - \sigma_y}{2} \sin 2\theta \qquad \text{...(ii)}$$

and resultant stress is given by

$$\sigma_R = \sqrt{(\sigma_n)^2 + \tau^2} = \sqrt{(\sigma_x \cos\theta)^2 + (\sigma_y \sin\theta)^2}$$

From equation (*i*), we see that the normal stress across the section EF will be maximum when $\cos 2\theta = 1$ or $\theta = 0°$. Therefore maximum normal stress when $\theta = 0°$ is σ_x. Similarly, the normal stress across the section EF will be minimum when $\cos 2\theta = -1$ or $2\theta = 180°$ or $\theta = 90°$. Therefore minimum normal stress when $\theta = 90°$ is σ_y. Thus we see that there are two principal planes at right angles to each other, one of which carries the maximum direct stress and the other minimum direct stress. These principal planes do not carry any shear stress.

From equation (*ii*), we see that the shear stress across the section EF will be maximum when $\sin 2\theta = 1$ or $2\theta = 90°$ or $270°$ or $\theta = 45°$ or $135°$. In other words, the shear stress will be maximum on two planes inclined at 45° and 135° to the normal section. Therefore maximum shear stress when $\theta = 45°$ or 135° is

$$\tau_{max} = \frac{\sigma_x - \sigma_y}{2}$$

2.24 Stresses on an Oblique Section of a Body in One Plane Accompanied by a Simple Shear Stress

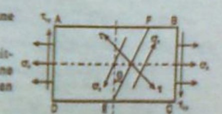


Fig. 2.9

When a body of uniform cross-sectional area and unit-thickness is subjected to a tensile stress (σ_x) in one plane accompanied by a shear stress (τ) as shown in Fig. 2.9, then the maximum normal stress is given by

$$(\sigma_n)_{max} = \frac{\sigma_x}{2} + \sqrt{\left(\frac{\sigma_x}{2}\right)^2 + (\tau_{xy})^2} = \frac{\sigma_x}{2} + \frac{1}{2}\sqrt{(\sigma_x)^2 + 4(\tau_{xy})^2}$$

Minimum normal stress,

$$(\sigma_n)_{min} = \frac{\sigma_x}{2} - \sqrt{\left(\frac{\sigma_x}{2}\right)^2 + (\tau_{xy})^2} = \frac{\sigma_x}{2} - \frac{1}{2}\sqrt{(\sigma_x)^2 + 4\,(\tau_{xy})^2}$$

and maximum shear stress,

$$\tau_{max} = \frac{(\sigma_n)_{max} - (\sigma_n)_{min}}{2} = \sqrt{\left(\frac{\sigma_x}{2}\right)^2 + (\tau_{xy})^2} = \frac{1}{2}\sqrt{(\sigma_x)^2 + 4\,(\tau_{xy})^2}$$

Note : When the expression $\frac{1}{2}\sqrt{(\sigma_x)^2 + 4\,(\tau_{xy})^2}$ is greater than $\frac{\sigma_x}{2}$, then the nature of $(\sigma_n)_{min}$ will be opposite to that of $(\sigma_n)_{max}$ [*i.e.* if $(\sigma_n)_{max}$ is tensile, $(\sigma_n)_{min}$ will be compressive and vice versa]

2.25 Stresses on an Oblique Section of a Body Subjected to Direct Stresses in Two Mutually Perpendicular Directions Accompanied by a Simple Shear Stress

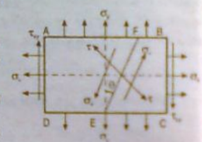


Fig. 2.10

When a body of uniform cross-sectional area and unit thickness is subjected to tensile stresses (σ_x and σ_y) in two mutually perpendicular planes accompanied by a simple shear stress (τ_{xy}), as shown in Fig. 2.10, then the maximum normal stress is given by

$$(\sigma_n)_{max} = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + (\tau_{xy})^2} = \frac{\sigma_x + \sigma_y}{2} + \frac{1}{2}\sqrt{(\sigma_x - \sigma_y)^2 + 4(\tau_{xy})^2}$$

Minimum normal stress,

$$(\sigma_n)_{min} = \frac{\sigma_x + \sigma_y}{2} - \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + (\tau_{xy})^2} = \frac{\sigma_x + \sigma_y}{2} - \frac{1}{2}\sqrt{(\sigma_x - \sigma_y)^2 + 4(\tau_{xy})^2}$$

and maximum shear stress,

$$\tau_{max} = \frac{(\sigma_n)_{max} - (\sigma_n)_{min}}{2} = \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + (\tau_{xy})^2}$$

$$= \frac{1}{2}\sqrt{(\sigma_x - \sigma_y)^2 + 4(\tau_{xy})^2}$$

2.26 Mohr's Circle of Stresses

The Mohr's circle is a graphical method of finding the normal, tangential and resultant stresses on an inclined plane. It is drawn for the following two cases:

(*a*) *When the two mutually perpendicular principal stresses are unequal and alike.* Let σ_x and σ_y be two unequal tensile (or compressive) principal stresses acting on a rectangular body. It is required to find the normal, tangential and resultant stresses on an oblique section making an angle θ with the minor tensile stress.

The Mohr's circle of stresses, as shown in Fig. 2.11, is drawn as discussed below :

1. Take $OA = \sigma_x$ and $OB = \sigma_y$ with some suitable scale on the same side of O (because the two stresses are alike).
2. Bisect BA at C. Now with C as centre and radius equal to CB or CA, draw a circle.
3. Through C, draw CP making an angle 2θ with CA and draw PQ perpendicular to OA. Join OP.
4. Now OQ and PQ will give the required normal and tangential stresses on the oblique section, to the scale. OP is the resultant stress. The angle POA is called the *angle of obliquity*.

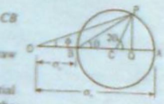


Fig. 2.11

Notes : 1. Since A and B are the ends of the horizontal diameter, therefore maximum normal stress will be equal to σ_x and the minimum principal stress will be σ_y.

2. The maximum shear stress will be equal to the radius of the Mohr's circle and will act on planes at 45° to the principal planes.

3. The angle of obliquity will be maximum when OP is tangential to the Mohr's circle.

(*b*) *When the two mutually perpendicular principal stresses are unequal and unlike.* Let σ_x be the principal tensile stress and σ_y be the principal compressive stress acting on a rectangular body. It is required to find the normal, tangential and resultant stresses on an oblique section making an angle θ.

The Mohr's circle of stresses, as shown in Fig. 2.12, is drawn as discussed below :

1. Take $OA = \sigma_x$ and $OB = \sigma_y$ with some suitable scale on the opposite sides of O (because the two stresses are unlike).
2. Bisect BA at C. Now with C as centre and radius equal to CB or CA, draw a circle.
3. Through C, draw CP making an angle 2θ with CA and draw PQ perpendicular to OA. Join OP.
4. Now OQ and PQ will give the required normal and tangential stresses on the oblique section, to the scale. OP is the required resultant stress, to the scale.

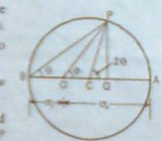


Fig. 2.12

2.27 Resilience

The strain energy stored in a body due to external loading within the elastic limit is known as *resilience*.

Notes : 1. The maximum strain energy which can be stored in a body upto the elastic limit is called *proof resilience*.

2. The proof resilience per unit volume of a material is known as *modulus of resilience*.

3. The strain energy stored in a body (or resilience) when it is subjected to direct tensile or compressive load

$$= \frac{\sigma^2}{2E} \times V$$

and modulus of resilience $= \frac{\sigma^2}{2E}$

where σ = Stress induced in the body,

E = Young's modulus for the material of the body, and

V = Volume of the body.

4. The strain energy stored in a body (or resilience) when it is subjected to shear stress (τ)

$$= \frac{\tau^2}{2C} \times V$$

and modulus of shear resilience

$$= \frac{\tau^2}{2C}$$

where C = Modulus of rigidity for the material of the body.

2.28 Stress Induced in a Body Under Different Modes of Loading

A load W may be applied to a body in the following three ways:

1. Gradually applied load, 2. Suddenly applied load, and

3. Falling load (also called impact or shock load).

When load W is applied gradually to a body, then the stress induced in a body is given by

$$\sigma = \frac{W}{A}$$

where A = Cross-sectional area of the body.

When load W is applied suddenly to a body, then the stress induced in body is *twice* the stress induced when the same load is applied gradually, *i.e.*

$$\sigma = 2 \times \frac{W}{A}$$

When load W is dropped from a height h, on to a body of length l and cross-sectional area A, then the stress induced (also called impact stress) is given by

$$\sigma_i = \frac{W}{A}\left[1 + \sqrt{1 + \frac{2h.A.E}{W.l}}\right]$$

2.29 Types of Beams

Following are the various types of beams :

1. *Cantilever beam.* A beam fixed at one end and free at the other end is known as a cantilever beam.

2. *Simply supported beam.* A beam supported at its both ends is known as simply supported beam.

3. *Overhanging beam.* A beam having its end portion extended beyond the support, is known as overhanging beam. A beam may be overhanging on one side or on both sides.

4. *Fixed beam.* A beam whose both ends are fixed, is known as fixed beam.

5. *Continuous beam.* A beam supported on more than two supports is known as continuous beam.

2.30 Types of Loading

A beam may be subjected to the following types of loads:

1. *Concentrated or point load.* A load acting at a point of a beam is known as a concentrated or point load.

2. *Uniformly distributed load.* A load which is spread over a beam in such a manner that each unit length is loaded to the some extent, is known as a uniformly distributed load (briefly written as U.D.L.).

3. *Uniformly varying load.* A load which is spread over a beam, in such a manner that it varies uniformly on each unit length, is known as uniformly varying load. Sometimes, the load is zero at one end and increases uniformly to the other. Such a load is known as triangular load.

2.31 Shear Force and Bending Moment Diagrams

The shear force (briefly written as S.F.) at the cross-section of a beam may be defined as the algebraic sum of all the forces on either side of the section.

The bending moment (briefly written as B.M.) at the cross-section of a beam may be defined as the algebraic sum of all the moments of the forces on either side of the section.

The following figures show the shear force and bending moment diagrams for different types of beams and loading.

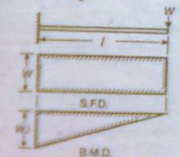


Fig. 2.13. Cantilever beam with a point load at the free end.

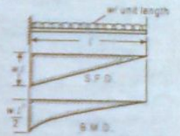


Fig. 2.14. Cantilever beam with uniformly distributed load (w/unit length).

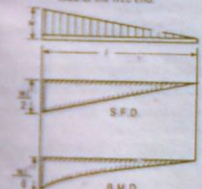


Fig. 2.15. Cantilever beam with gradually varying load.

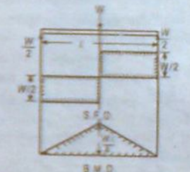


Fig. 2.16. Simply supported beam with point load at its mid point.

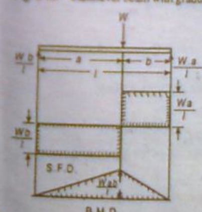


Fig. 2.17. Simply supported beam with an eccentric point load.

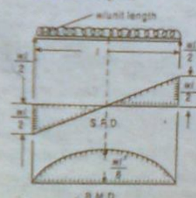


Fig. 2.18. Simply supported beam with a U.D.L.

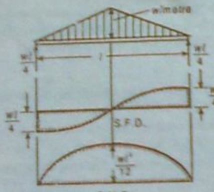


Fig 2.19. Simply supported beam with a triangular load varying gradually from zero at both ends to w per metre at the centre.

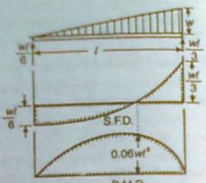


Fig 2.20. Simply supported beam with a gradually varying load, from zero at one end to w per metre at the other end.

Notes : 1. The bending moment is maximum where shear force diagram changes sign from positive to negative or vice versa. In other words, the bending moment is maximum at a point where shear force is zero.

2. The point where the bending moment changes sign (or zero) is known as *point of contraflexure*. This point generally occurs in overhanging beams.

2.32 Assumptions in Theory of Bending

The following assumptions are made in the theory of simple bending:

1. The material of the beam is perfectly homogeneous (*i.e.* of the same kind throughout) and isotropic (*i.e.* of equal elastic properties in all directions).
2. The beam material is stressed within its elastic limit and thus obey's Hooke's law.
3. The transverse sections which are plane before bending, remain plane after bending also.
4. Each layer of the beam is free to expand or contract independently of the layer, above or below it.
5. The value of Young's modulus for the material of beam is same in tension and compression.

2.33 Bending Equation for Beams in Simple Bending

The following is the bending equation for beams in simple bending :

$$\frac{M}{I} = \frac{\sigma}{y} = \frac{E}{R}$$

where M = Bending moment,

I = Moment of inertia of the area of cross-section,

σ = Bending stress,

y = Distance of extreme fibre from the neutral axis,

E = Young's modulus for the material of the beam, and

R = Radius of curvature.

Notes : 1. The line of intersection of the neutral layer with any normal cross-section of a beam is known as *neutral axis* of that section.

2. On one side of the neutral axis there are compressive stresses, and on the other side there are tensile

stresses. At neutral axis there is no stress of any kind. The neutral axis of a section always passes through its centroid.

3. Since there are compressive stresses on one side of the neutral axis and tensile stresses on the other side, therefore these stresses form a couple whose moment must be equal to the external moment M. The moment of this couple which resist the external bending moment, is known as *moment of resistance*.

4. From the bending equation $\frac{M}{I} = \frac{\sigma}{y}$, we have

$$M = \sigma \times \frac{I}{y} \quad \text{or} \quad M = \sigma \times Z$$

where Z is known as section modulus or modulus of section.

2.34 Beams of Uniform Strength

A beam in which bending stress developed is constant and is equal to the allowable stress, is called a *beam of uniform strength*. It can be achieved by

1. Keeping the width uniform and varying the depth.
2. Keeping the depth uniform and varying the width.
3. Varying the width and depth both.

The common method of obtaining the beam of uniform strength is by keeping the width uniform and varying the depth.

2.35 Beams of Composite Section (Flitched Beams)

A beam made up of two or more different materials joined together in such a manner that they behave like a unit piece, is called a *composite beam* or *flitched beam*. Such beams are used when one material, if used alone, requires a larger cross-sectional area which is not suited to the space available and also to reinforce the beam at regions of high bending moment or to equalise the strength of the beam in tension or compression.

A beam of two materials, as shown in Fig. 2.21, is most common, such as wooden beam reinforced by metal strips and concrete beams reinforced with steel rods. In such cases, the total moment of resistance will be equal to the sum of the moment of resistances of the individual sections, *i.e.*

Fig. 2.21

$$M = M_1 + M_2 = \sigma_1 . Z_1 + \sigma_2 . Z_2 \quad \text{...(i)}$$

We also know that at any distance, from the neutral axis, strain in both the materials will be same, *i.e.*

$$\frac{\sigma_1}{E_1} = \frac{\sigma_2}{E_2} \quad \text{or} \quad \sigma_1 = \frac{E_1}{E_2} \times \sigma_2 = m . \sigma_2 \quad \text{...(ii)}$$

From the above two relations, we can find out the moment of resistance of a composite beam or the stresses in the two materials.

2.36 Shear Stresses in Beams

The maximum shear stress developed in a beam of rectangular cross-section, as shown in Fig. 2.22, is given by

$$\tau_{max} = 1.5\,\tau_{av}$$

where τ_{av} = Average shear stress = Load / Area

The maximum shear stress developed in a beam of circular cross-section, as shown in Fig. 2.23, is given by

$$\tau_{max} = \frac{4}{3}\,\tau_{av}$$

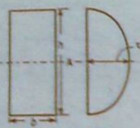


Fig. 2.22

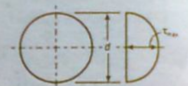


Fig. 2.23

It may be noted that the shear stress in a beam is not uniformly distributed over the cross-section, but varies from zero at outer fibres to a maximum at the neutral surface as shown in Fig 2.22 and Fig. 2.23.

2.37 Deflection of Beams

The general equation for the deflection of beams is

$$M = EI\,\frac{d^2y}{dx^2}$$

where

M = Bending moment,

E = Young's modulus, and

I = Moment of inertia.

The product of $E.I$ is known as *flexural rigidity*. Let us now consider the following cases :

1. *Simply supported beam with a central point load.* A simply supported beam AB of length l and carrying a point load at the centre of the beam at C is shown in Fig. 2.24. The deflection at point C (it is the maximum deflection) is

$$y_C = \frac{wl^3}{48\,EI}$$

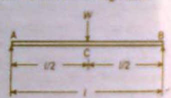


Fig. 2.24

2. *Simply supported beam with an eccentric point load.* A simply supported beam AB of length l and carrying an eccentric point load at C is shown in Fig. 2.25. The deflection at point C is given by

$$y_C = \frac{Wab}{6EIl}\,(l^2 - a^2 - b^2) = \frac{Wa^2b^2}{3EIl}$$

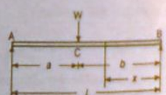


Fig. 2.25

Since $b > a$, therefore maximum deflection occurs in CB and its distance from B is given by

$$x = \sqrt{\frac{l^2 - a^2}{3}}$$

and maximum deflection,

$$y_{max} = \frac{W.a}{9\sqrt{3}\,EIl}\,(l^2 - a^2)^{3/2}$$

3. *Simply supported beam with a uniformly distributed load.* A simply supported beam AB with a uniformly distributed load w / unit length is shown in Fig. 2.26.

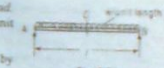


Fig. 2.26

The maximum deflection occurs at the mid point C and is given by

$$y_C = \frac{5wl^4}{384\,EI} = \frac{5Wl^3}{384\,EI} \qquad (\because W = w.l)$$

4. *Simply supported beam with a gradually varying load.* A simply supported beam AB of length l and carrying a gradually varying load from zero at B to w / unit length at A, is shown in Fig. 2.27.

Fig. 2.27

The deflection at any section X of the beam at a distance x from B is given by

$$y = \frac{1}{EI} \times \left(\frac{wlx^3}{36} - \frac{wx^5}{120l} - \frac{7wl^3x}{360}\right)$$

The maximum deflection occurs when $x = 0.519\,l$ and its value is given by

$$y_{max} = \frac{0.006\,52\;wl^4}{EI}$$

5. *Cantilever beam with a point load at the free end.* A cantilever beam AB of length l carrying a point load at the free end is shown in Fig 2.28. The deflection at any section X at a distance x from the free end is given by

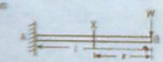


Fig. 2.28

$$y = \frac{1}{EI}\left(\frac{wl^2x}{2} - \frac{wx^3}{6} - \frac{wl^3}{3}\right)$$

The maximum deflection occurs at the free end (when $x = 0$) and its value is given by

$$y_B = \frac{Wl^3}{3EI}$$

6. *Cantilever beam with a uniformly distributed load.* A cantilever beam AB of length l carrying a uniformly distributed load w / unit length is shown in Fig. 2.29. The deflection at any section X at a distance x from B is given by

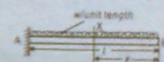


Fig. 2.29

$$y = \frac{1}{EI}\left(\frac{wl^3x}{6} - \frac{wx^4}{24} - \frac{wl^4}{8}\right)$$

The maximum deflection occurs at the free end (when $x = 0$) and its value is given by

$$y_B = \frac{wl^4}{8EI} = \frac{Wl^3}{8EI} \qquad (\because W = w.l)$$

When a cantilever is partially loaded as shown in Fig. 2.30, then the deflection at point C (at a distance l_1 from the fixed end) is given by

$$y_C = \frac{wl_1^4}{8EI}$$

and the maximum deflection occurs at B whose value is given by

$$y_B = \frac{7Wl^4}{384\,EI}$$

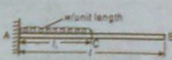


Fig. 2.30

7. *Cantilever beam with a gradually varying load.* A cantilever beam AB of length l carrying a gradually varying load from zero at B to w / unit length at A is shown in Fig. 2.31. The deflection at any section X at a distance x from B is given by

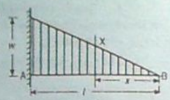


Fig 2.31

$$y = \frac{1}{EI}\left(\frac{wl^3 x}{24} - \frac{wx^5}{120l} - \frac{wl^4}{30}\right)$$

The maximum deflection occurs at the free end (when $x = 0$) and its value is given by

$$y_B = \frac{wl^4}{30\,EI}$$

8. *Fixed beam carrying a central point load.* A fixed beam AB of length l carrying a point load at the centre of the beam at C is shown in Fig. 2.32. The maximum deflection occurs at C and its value is given by

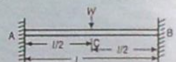


Fig 2.32

$$y_C = \frac{Wl^3}{192\,EI}$$

9. *Fixed beam carrying an eccentric point load.* A fixed beam AB of length l carrying an eccentric point load at C is shown in Fig. 2.33. The deflection at any section X at a distance x from A is given by

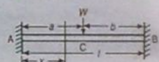


Fig 2.33

$$y = \frac{Wb^2x^2}{6EIl^3}\left[x(3a+b) - 3al\right]$$

The maximum deflection occurs when $x = \dfrac{2al}{3a+b}$

∴ Maximum deflection,

$$y_{max} = \frac{2}{3} \times \frac{Wa^2b^2}{EI\,(3a+b)^2}$$

and deflection under the load at C,

$$y_C = \frac{Wa^3b^3}{3EIl^3}$$

10. *Fixed beam carrying a uniformly distributed load.* A fixed beam AB of length l carrying a uniformly distributed load of w / unit length is shown in Fig. 2.34. The deflection at any section X at a distance x from A is given by

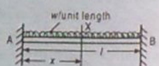


Fig 2.34

$$y = \frac{1}{EI}\left(\frac{w.l.x^3}{12} - \frac{w.x^4}{24} - \frac{wl^2x^2}{24}\right)$$

The maximum deflection occurs at the centre of the beam and its value is given by

$$y_{max} = \frac{wl^4}{384\,EI} = \frac{Wl^3}{384\,EI} \qquad \ldots(\because W = w.l)$$

2.38 Shear Stress in Shafts

When a shaft fixed at one end is subjected to a torque (or twisting moment) at the other end, then every cross-section of the shaft will be subjected to shear stresses. It may be noted that the

shear stress is zero at the centroidal axis of the shaft and maximum at the outer surface. The maximum shear stress at the outer surface of the shaft may be obtained by the following equation, known as torsion equation.

$$\frac{\tau}{R} = \frac{T}{J} = \frac{C\theta}{l} \qquad \ldots(i)$$

where
- τ = Shear stress induced at the outer surface of the shaft or maximum shear stress,
- R = Radius of the shaft,
- T = Torque or twisting moment,
- J = Polar moment of inertia. It is the second moment of area of the section about its polar axis $= I_{xx} + I_{yy}$
- C = Modulus of rigidity for the shaft material,
- l = Length of the shaft, and
- θ = Angle of twist in radians on a length l.

The above equation is based on the following assumptions :

1. The material of the shaft is uniform throughout.
2. The twist along the shaft is uniform.
3. The normal cross-section of the shaft, which were plane and circular before twist, remain plane and circular after twist.
4. All diameters of the normal cross-section which were straight before twist, remain straight with their magnitude unchanged, after twist.

The following points may be noted :

1. The shear stress on any cross-section normal to the axis of the shaft is directly proportional to the distance from the centre of the shaft. Thus shear stress at a distance x from the centre of the shaft is given by

$$\frac{\tau_x}{x} = \frac{\tau}{R}$$

2. The strength of a shaft means the maximum torque or power transmitted by the shaft. From equation (i), we have

$$\frac{\tau}{R} = \frac{T}{J} \quad \text{or} \quad T = \tau \times \frac{J}{R}$$

For a solid shaft of diameter (D), the polar moment of inertia,

$$J = I_{xx} + I_{yy} = \frac{\pi D^4}{64} + \frac{\pi D^4}{64} = \frac{\pi D^4}{32}$$

$$\therefore \quad T = \tau \times \frac{\pi D^4}{32} \times \frac{2}{D} = \frac{\pi}{16} \times \tau D^3$$

For a hollow shaft with external diameter (D) and internal diameter (d), the polar moment of inertia,

$$J = \frac{\pi}{32}(D^4 - d^4), \quad \text{and} \quad r = \frac{D}{2}$$

$$\therefore \quad T = \frac{\pi}{16} \times \tau\left(\frac{D^4 - d^4}{D}\right) = \frac{\pi}{16} \times \tau \times D^3(1 - k^4) \text{ where } k = \frac{d}{D}$$

3. The term J/R is known as polar modulus. The polar modulus for a solid shaft,

$$Z_p = \frac{\pi}{16} D^3$$

and polar modulus for a hollow shaft,

$$Z_p = \frac{\pi}{16}\left(\frac{D^4 - d^4}{D}\right)$$

4. The term T/θ is known as *torsional rigidity* of the shaft.
5. The power transmitted by a shaft (in watts) is given by

$$P = T.\omega = \frac{2\pi N T}{60} \qquad \left(\because \omega = \frac{2\pi N}{60}\right)$$

where T = Torque transmitted in N-m,
N = Speed of the shaft in r.p.m., and
ω = Angular speed in rad/s.

2.39 Strain Energy due to Torsion

The total strain energy stored in a solid shaft of diameter D and length l is given by

$$U = \frac{\tau^2}{4C} \times V$$

where V = Volume of the shaft $= \frac{\pi}{4} \times D^2 \times l$

and total strain energy stored in a hollow shaft of external diameter (D) and internal diameter (d) is given by

$$U = \frac{\tau^2}{4C}\left(\frac{D^2 + d^2}{D^2}\right)V$$

2.40 Shaft Subjected to Combined Bending and Torsion

When a shaft is subjected to a twisting moment or torque (T) and a bending moment (M) due to self weight of the shaft and pulleys mounted on it, then the maximum normal stress in the shaft is given by

$$\sigma_{b(max)} = \frac{1}{2}\left(\sigma_b + \sqrt{(\sigma_b^2) + 4\tau^2}\right) \qquad ...(i)$$

and minimum normal stress,

$$\sigma_{b(min)} = \frac{1}{2}\left(\sigma_b - \sqrt{(\sigma_b)^2 + 4\tau^2}\right) \qquad ...(ii)$$

where σ_b = Bending stress induced in the shaft due to bending moment (M), and
τ = Shear stress induced in the shaft due to twisting moment (T).

We know that for a shaft of diameter (D),

$$\sigma_b = \frac{32M}{\pi D^3}, \text{ and } \tau = \frac{16T}{\pi D^3}$$

Substituting these values in equations (i) and (ii),

Maximum normal stress,

$$\sigma_{b(max)} = \frac{32}{\pi D^3}\left[\frac{1}{2}\left(M + \sqrt{M^2 + T^2}\right)\right] = \frac{16}{\pi D^3}\left[M + \sqrt{M^2 + T^2}\right]$$

and minimum normal stress,

$$\sigma_{b(min)} = \frac{32}{\pi D^3}\left[\frac{1}{2}\left(M - \sqrt{M^2 + T^2}\right)\right] = \frac{16}{\pi D^3}\left[M - \sqrt{M^2 + T^2}\right]$$

The expression $\left[\frac{1}{2}\left(M + \sqrt{M^2 + T^2}\right)\right]$ is known as *equivalent bending moment* and is denoted by M_e. The equivalent bending moment is defined as that bending moment which when acting alone produces the same tensile or compressive stress (σ_b) as the actual bending moment.

We know that maximum shear stress in the shaft

$$\tau_{max} = \frac{\sigma_{b(max)} - \sigma_{b(min)}}{2} = \frac{1}{2}\sqrt{(\sigma_b)^2 + \tau^2} = \frac{16}{\pi D^3}\left(\sqrt{M^2 + T^2}\right)$$

The expression $\sqrt{M^2 + T^2}$ is known *as equivalent twisting moment* and is denoted by T_e. The equivalent twisting moment is defined as that twisting moment which when acting alone produces the same shear stress (τ) as the actual twisting moment.

Note : For a hollow shaft of external diameter (D) and internal diameter (d), the maximum normal stress,

$$\sigma_{b(max)} = \frac{16D}{\pi(D^4 - d^4)}\left(M + \sqrt{M^2 + T^2}\right)$$

Minimum normal stress,

$$\sigma_{b(min)} = \frac{16D}{\pi(D^4 - d^4)}\left(M - \sqrt{M^2 + T^2}\right)$$

and maximum shear stress,

$$\tau_{max} = \frac{16D}{\pi(D^4 - d^4)}\left(\sqrt{M^2 + T^2}\right)$$

2.41 Springs

A spring is a device whose function is to distort when loaded and to recover its original shape when the load is removed. The various important applications of springs are as follows:

1. To cushion, absorb or control energy due to either shock or vibration as in car springs, railway buffers, shock absorbers and vibration dampers.
2. To apply forces as in brakes, clutches and spring loaded valves.
3. To control motion by maintaining contact between two elements as in cams and followers.
4. To measure forces as in spring balances and engine indicators.
5. To store energy as in watches, toys etc.

2.42 Stiffness of a Spring

The load required to produce a unit deflection in a spring is called stiffness of a spring.

2.43 Carriage Spring or Leaf Springs

The maximum bending stress developed in the spring is given by

$$\sigma = \frac{3Wl}{2nbt^2}$$

and deflection,

$$\delta = \frac{3Wl^3}{8Enbt^3}$$

where

W = Load on the spring,

l = Span of the spring,

t = Thickness of the plates,

b = Width of the plates,

n = Number of plates, and

E = Young's modulus for the material of the plates.

2.44 Closely Coiled Helical Springs

When a closely coiled helical spring of mean diameter (D) is subjected to an axial load W, then the twisting moment due to the load W is given by

$$T = W.R = W \times \frac{D}{2} = \frac{\pi}{16} \times \tau \times d^3$$

Deflection of the spring,

$$\delta = \frac{64WR^3n}{Cd^4} = \frac{8\,WD^3n}{Cd^4}$$

Energy stored in the spring,

$$U = \frac{1}{2}\,W.\delta$$

and stiffness of the spring,

$$s = \frac{W}{\delta} = \frac{Cd^4}{64\,R^3n} = \frac{Cd^4}{8\,D^3\,n}$$

where

R = Mean radius of the spring coil = $D/2$

d = Diameter of the spring wire,

n = Number of turns or coils,

C = Modulus of rigidity for the spring material,

τ = Maximum shear stress induced in the wire due to twisting.

2.45 Springs in Series and Parallel

When two springs having stiffness k_1 and k_2 are connected in series as shown in Fig. 2.35. (*a*), then the combined stiffness of the springs (k) is given by

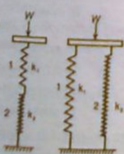


Fig. 2.35

$$\frac{1}{k} = \frac{1}{k_1} + \frac{1}{k_2}$$

When the springs are connected in parallel as shown in Fig. 2.35 (*b*), then

$$k = k_1 + k_2$$

2.46 Riveted Joints

Following are two types of riveted joints, depending upon the way in which the members are connected:

1. Lap joint, and 2. Butt joint

A *lap joint* is that in which one plate overlaps the other and the two plates are riveted together.

A butt joint is that in which the main plates are kept in alignment butting (*i.e.* touching) each other and a cover plate (*i.e.* strap) is placed on one side or on both sides of the main plates. The cover plate is then riveted together with the main plates. Butt joints are of the following two types:

1. Single strap butt joint, and 2. Double strap butt joint.

In a *single strap butt joint*, the edges of the main plates butt against each other and only one cover plate is placed on one side of the main plates and then riveted together.

In a *double strap butt joint*, the edges of the main plates butt against each other and two cover plates are placed on both sides of the main plates and then riveted together.

In addition to the above, following are the types of riveted joints depending upon the number of rows of the rivets.

1. Single riveted joint, and 2. Double riveted joint.

A *single riveted joint* is that in which there is a single row of rivets in a lap joint and there is a single row of rivets on each side in a butt joint.

A *double riveted joint* is that in which there are two rows of rivets in a lap joint and there are two rows of rivets on each side in a butt joint.

Similarly the joints may be triple riveted or quadruple riveted.

Note: When the rivets in the various rows are opposite to each other, then the joint is said to be *chain riveted*. On the other hand, if the rivets in the adjacent rows are staggered in such a way that every rivet is in the middle of the two rivets of the opposite row, then the joint is said to be *zig-zag riveted*.

2.47 Important Terms Used in Riveted Joints

Following are important terms used in riveted joints:

1. *Pitch.* It is the distance from the centre of one rivet to the centre of the next rivet measured parallel to the seam.

2. *Back pitch.* It is the perpendicular distance between the centre lines of the successive rows.

3. *Diagonal pitch.* It is the distance between the centres of the rivets in adjacent rows of zig zag riveted joint.

4. *Margin or marginal pitch.* It is the distance between the centre of rivet hole to the nearest edge of the plate.

2.48 Failures of Riveted Joints

A riveted joint may fail in the following ways:

1. *Tearing of the plate at an edge.* This can be avoided by keeping the margin $(m) = 1.5\,d$, where d is the diameter of rivet hole.

2. *Tearing of the plate across the row of rivets.* The tearing resistance or pull required to tear off the plate per pitch length is given by

$$P_t = (p - d)\,t.\,\sigma_t$$

where
p = Pitch of the rivets,
d = Diameter of the rivet hole.
t = Thickness of the plate, and
σ_t = Permissible tensile stress for the plate material.

3. *Shearing of rivets.* The shearing resistance or pull required to shear off the rivet per pitch length is given by

$$P_s = n \times \frac{\pi}{4} d^2 \times \tau \quad \text{...(in single shear)}$$

$$= n \times 2 \times \frac{\pi}{4} d^2 \times \tau \quad \text{...(in double shear)}$$

where
n = Number of rivets per pitch length, and
τ = Permissible shear stress for the rivet material.

4. *Crushing of rivets.* The crushing resistance or pull required to crush the rivet per pitch length is given by

$$P_c = n.\,d.\,t.\,\sigma_c$$

where
σ_c = Permissible crushing stress for the rivet material.

Notes : 1. The strength of the riveted joint is equal to the least value of P_t, P_s and P_c.

2. The ratio of strength of the riveted joint to the strength of the unriveted plate per pitch length is called efficiency of the riveted joint. Mathematically, efficiency of the riveted joint,

$$\eta = \frac{\text{Least value of } P_t, P_s \text{ and } P_c}{p.\,t.\,\sigma_t}$$

2.49 Welded Joints

The strength of the transverse fillet welded joints is given by

$$P = \frac{1}{\sqrt{2}}\, s.\,l.\,\sigma_t \quad \text{...(For single fillet weld)}$$

$$= \sqrt{2}\, s.\,l.\,\sigma_t \quad \text{.... (For double fillet weld)}$$

where
s = Leg or size of weld,
l = Length of weld, and
σ_t = Allowable tensile stress for the weld metal.

The strength of parallel fillet welded joints is given by

$$P = \frac{1}{\sqrt{2}}\, s.\,l.\,\tau \quad \text{... (For single parallel fillet weld)}$$

$$= \sqrt{2}\, s.\,l.\,\tau \quad \text{... (For double parallel fillet weld)}$$

Note : The transverse fillet welded joints are designed for tensile strength and parallel fillet welded joints are designed for shear strength.

2.50 Thin Cylindrical and Spherical Shells

- If the thickness of the wall of a shell is less than 1 / 10 to 1 / 15 of its diameter, it is known as *thin shell.* It may be noted that whenever a cylindrical shell is subjected to an internal pressure, its walls are subjected to the following two types of tensile stresses:

1. Circumferential stress or hoop stress, and 2. Longitudinal stress.

In case of thin shells, the stresses are assumed to be uniformly distributed throughout the wall thickness. When a thin cylindrical shell of diameter (d), thickness (t) and length (l) is subjected to an internal pressure (p), then the circumferential or hoop stress induced in the shell,

$$\sigma_c = \frac{p.\,d}{2t.\,\eta}$$

and longitudinal stress,

$$\sigma_l = \frac{p.\,d}{4t.\,\eta}$$

where
η = Efficiency of the riveted joint, when the shell is made of desired capacity by joining different plates, by means of rivets.

Notes : 1. The circumferential stress has the tendency to split up the cylindrical shell into two troughs.

2. The longitudinal stress has the tendency to split up the cylindrical shell into two cylinders.

3. The longitudinal stress is half of the circumferential or hoop stress.

2.51 Change in Dimensions of a Thin Cylindrical Shell

When a thin cylindrical shell is subjected to an internal pressure, its walls will be subjected to lateral strain, the effect of which is to cause some change in the dimensions (*i.e.* length and diameter) of the shell. The circumferential strain is given by

$$\varepsilon_c = \frac{p.\,d}{2t\,E}\left(1 - \frac{1}{2m}\right)$$

and longitudinal strain,

$$\varepsilon_l = \frac{p.\,d}{2t\,E}\left(\frac{1}{2} - \frac{1}{m}\right)$$

where
E = Young's modulus for the shell material, and
$1/m$ = Poisson's ratio.

The change in diameter is given by

$$\delta d = \varepsilon_c.\,d = \frac{p.\,d^2}{2t\,E}\left(1 - \frac{1}{2m}\right)$$

and change in length,

$$\delta l = \varepsilon_l.\,l = \frac{p.\,d\,l}{2t\,E}\left(\frac{1}{2} - \frac{1}{m}\right)$$

It may be noted that when the shell is subjected to an internal pressure, there will be an increase in the diameter as well as the length of the shell.

The change in volume is given by

$$\delta V = V\,(2\varepsilon_c + \varepsilon_l),\ \text{where } V = \frac{\pi}{4} \times d^2 \times l$$

and volumetric strain,
$$\frac{\delta V}{V} = 2\varepsilon_c + \varepsilon_l = \frac{p.d}{4tE}\left(5 - \frac{4}{m}\right)$$

2.52 Thin Spherical Shells

When a thin spherical shell of diameter (d) and thickness (t) is subjected to an internal pressure (p), then the stress induced in the shell material,

$$\sigma = \frac{p.d}{4\,t\,\eta}$$

The change in diameter is given by

$$\delta d = \frac{p.d^2}{4tE}\left(1 - \frac{1}{m}\right)$$

and change in volume,
$$\delta V = \frac{\pi p d^4}{8tE}\left(1 - \frac{1}{m}\right)$$

2.53 Thick Cylindrical and Spherical Shells

If the thickness of the wall of a shell is greater than 1 / 10 to 1 / 15 of its diameter, it is known as *thick shell*. The thick shells are, generally, used to withstand high pressures. Sometimes, even, compound thick shells are used to withstand very high pressures or to contain chemicals under high pressure.

The problem of thick cylinders is, somewhat, complex and is solved by *Lame's theory*.

2.54 Direct and Bending Stresses

When an eccentric load acts upon a body, then the direct and bending stresses are induced. Consider a column subjected to a compressive load P acting at an eccentricity of e as shown in Fig. 2.36.

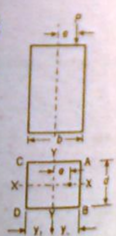


Fig. 2.36

The magnitude of direct compressive stress over the entire cross-section of the column is given by

$$\sigma_o = P / A$$

where A = Cross-sectional area of the column.

The magnitude of bending stress at the edge AB is given by

$$\sigma_b = \frac{P.e.y_c}{I} \quad \text{(compressive)}$$

and bending stress at the edge CD,

$$\sigma_b = \frac{P.e.y_t}{I} \quad \text{(tensile)}$$

where y_c and y_t = Distances of the extreme fibres on the compressive and tensile sides, from the neutral axis respectively, and

I = Second moment of area of the section about the neutral axis *i.e.* Y-axis = $db^3/12$.

The maximum or resultant compressive stress at the edge AB is given by

$$\sigma_c = \frac{P.e.y_c}{I} + \frac{P}{A} = \frac{M}{Z} + \frac{P}{A} = \sigma_b + \sigma_o$$

$$\ldots (\because M = P.e,\ \text{and } Z = I / y_c)$$

and the maximum or resultant tensile stress at the edge CD is

$$\sigma_t = \frac{P.e.y_t}{I} - \frac{P}{A} = \frac{M}{Z} - \frac{P}{A} = \sigma_b - \sigma_o$$

Notes : 1. When the member is subjected to a tensile load, then the above equations may be used by interchanging the subscripts c and t.

2. When the direct stress σ_o is greater than or equal to bending stress σ_b, then the compressive stress shall be present all over the cross-section.

3. When the direct stress σ_o is less than the bending stress σ_b, then the tensile stress will occur in the left hand portion of the cross-section and compressive stress on the right hand portion of the cross-section.

2.55 Limit of Eccentricity

It is the maximum distance between the geometrical axis of a column section and the point of loading such that no tensile stress comes into play at any section of the column. We have seen above that the resultant tensile stress at the edge CD,

$$\sigma_t = \sigma_b - \sigma_o = \frac{M}{Z} - \frac{P}{A}$$

If the tensile stress is not to be permitted to come into play, then the bending stress (σ_b) should be less than the direct stress (σ_o) or at the most, it may be equal to the direct stress, *i.e.*

$$\sigma_b \le \sigma_o \quad \text{or} \quad \frac{M}{Z} \le \frac{P}{A} \quad \text{or} \quad \frac{P.e}{Z} \le \frac{P}{A} \quad \text{or} \quad e \le \frac{Z}{A}$$

The limit of eccentricity (e) for various sections is as follows :

1. For a rectangular section of width (b) and depth (d), $e \le d/6$
2. For a hollow rectangular section with B and D outer width and depth respectively and b and d inner width and depth respectively,

$$e \le \frac{BD^3 - bd^3}{6D\,(BD - bd)}$$

3. For a circular section of diameter (d), $e \le d/8$
4. For a hollow circular section of outer and inner diameter D and d respectively,

$$e \le \frac{D^2 + d^2}{8D}$$

2.56 Columns and Struts

A structural member, subjected to an axial compressive force, is called a *strut*. A strut may be horizontal, inclined or even vertical. But a vertical strut, used in buildings or frames, is called a *column*.

According to Euler's column theory, the critical load (P) on the column for different types of end conditions is as follows :

1. For both ends hinged, $P = \dfrac{\pi^2 EI}{l^2}$
2. For one end fixed and other end free, $P = \dfrac{\pi^2 EI}{4l^2}$
3. For both ends fixed, $P = \dfrac{4\pi^2 EI}{l^2}$
4. For one end fixed and other end hinged, $P = \dfrac{2\pi^2 EI}{l^2}$

In general, Euler's formula is given by

$$P = \frac{\pi^2 EI}{Cl^2}$$

where C is a constant, representing the end condition of the column. It may be noted that

(*a*) $C = 1$, for a column with both ends hinged.

(*b*) $C = 4$, for a column with one end fixed and other end free.

(*c*) $C = 1/4$, for a column with both ends fixed.

(*d*) $C = 1/2$, for a column with one end fixed and the other end hinged.

There is another way of representing the Euler's formula, for the crippling load, by an equivalent length or effective length of a column. The equivalent length, of a given column with given end conditions, is the length of an equivalent column of the same material and cross-section with hinged ends and having the value of crippling load equal to that of the given column.

The equivalent lengths (L) for the given end conditions are given in the following Table.

S. No.	*End conditions*	*Crippling load*	*Relation between equivalent length and actual length*
1.	Both ends hinged	$\dfrac{\pi^2 EI}{l^2} = \dfrac{\pi^2 EI}{L^2}$	$L = l$
2.	One end fixed and the other end free	$\dfrac{\pi^2 EI}{4l^2} = \dfrac{\pi^2 EI}{(2l)^2} = \dfrac{\pi^2 EI}{L^2}$	$L = 2l$
3.	Both ends fixed	$\dfrac{4\pi^2 EI}{l^2} = \dfrac{\pi^2 EI}{\left(\frac{l}{2}\right)^2} = \dfrac{\pi^2 EI}{L^2}$	$L = \dfrac{l}{2}$
4.	One end fixed and the other end hinged	$\dfrac{2\pi^2 EI}{l^2} = \dfrac{\pi^2 EI}{\left(\frac{l}{\sqrt{2}}\right)^2} = \dfrac{\pi^2 EI}{L^2}$	$L = \dfrac{l}{\sqrt{2}}$

Notes : 1. *The vertical column will have two moments of inertia* (*i.e.* I_{xx} *and* I_{yy}). *Since the column will tend to buckle in the direction of least moment of inertia, therefore the least value of the two moments of inertia is to be used in the Euler's formula.*

2. The Euler's formula is given by

$$P = \frac{\pi^2 EI}{l^2} = \frac{\pi^2 E\,Ak^2}{l^2} = \frac{\pi^2 EA}{(l/k)^2}$$

... ($\because$ $I = A.k^2$, where A is the area and k is the least radius of gyration of the section)

3. The ratio l/k is known as *slenderness ratio*.

4. Sometimes, the columns whose slenderness ratio is more than 80, are known as *long columns* and those whose slenderness ratio is less than 80 are known as *short columns*.

5. Euler's formula holds good only for long columns.

2.57 Rankine's Formula For Columns

The Rankine's formula for crippling load (P) is given by

$$P = \frac{\sigma_c . A}{1 + a\left(\frac{L}{k}\right)^2}$$

where
- σ_c = Crushing stress of the column material,
- A = Cross-sectional area of the column,
- a = Rankine's constant = $\dfrac{\sigma_c}{\pi^2 E}$
- L = Equivalent length of the column, and
- k = Least radius of gyration.

The values of Rankine's constant (a) are as follows :

1.	For wrought iron,	$a = 1/9000$;	2.	For mild steel,	$a = 1/7500$
3.	For cast iron,	$a = 1/1600$	4.	For timber	$a = 1/750$

2.58 Dams and Retaining Walls

A dam is constructed to store large quantity of water, which is used for the purpose of irrigation and power generation. A dam constructed with earth is called an *earthen dam* whereas a dam constructed with cement concrete is called *masonry* or *gravity dam*. A dam may be of any cross-section, but the dams of trapezoidal cross-section are very popular these days. A retaining wall is generally constructed to retain earth in hilly areas.

The following two forces generally act on a dam :

1. The weight of the dam acting downward; and
2. The pressure of water acting horizontally.

Consider a trapezoidal dam of unit length having its water face vertical as shown in Fig. 2.37.

Let
- a = Top width of dam,
- b = Bottom width of dam,
- H = Height of dam,
- ρ = Specific weight of the dam masonry,
- h = Height of water retained by the dam, and
- w = Specific weight of water.

We know that weight of the dam per unit length,

$$W = \frac{a+b}{2} \times H \times 1 \times \rho$$

and total pressure on a unit length of a trapezoidal dam,

$$P = \frac{w.h^2}{2}$$

Horizontal distance between C.G. of the dam and the point where resultant R cuts the base (*i.e.* distance JK)

$$= \frac{P}{W} \times \frac{h}{3}$$

Distance between the toe of the dam A and the point where the resultant R cuts the base (*i.e.* distance AK),

$$x = AJ + JK = AJ + \frac{P}{W} \times \frac{h}{3}$$

Resolving the resultant R acting at point K into two components *i.e.* the horizontal component (P) and the vertical component (W). The horizontal component does not affect the stresses at the base.

The stresses which are developed at the base of the dam are, therefore, due to the weight of the dam (W), which acts with an eccentricity OK where O is the mid point of AB. From Fig. 2.37, we find that eccentricity

$$OK = e = AK - AO = AJ + JK - \frac{b}{2}$$

The maximum stress (σ_{max}) occurs across the base at B and minimum stress (σ_{min}) occurs at A, such that

$$\sigma_{max} = \frac{W}{b}\left(1 + \frac{6e}{b}\right)$$

and

$$\sigma_{min} = \frac{W}{b}\left(1 - \frac{6e}{b}\right)$$

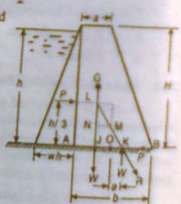


Fig. 2.37

2.59 Conditions for Stability of a Dam

A masonry dam may fail due to

1. Tension in the masonry at the base of the dam,
2. Overturning of the dam,
3. Sliding of the dam, and
4. Crushing of masonry at the base of the dam.

Following conditions must be satisfied for the stability of a dam :

1. In order to avoid tension in the masonry of the dam at its base, the resultant must lie within the middle third of the base width.

2. When the resultant lies within middle third of the base width, the overturning of the dam is also avoided.

3. In order to avoid sliding of the masonry dam, the force of friction betwen the dam and the soil should be at least 1.5 times the total water pressure per metre length.

4. In order to prevent the crushing of masonry at the base of the dam, the maximum stress should be less than the permissible stress in the masonry.

2.60 Active Earth Pressure

The pressure, exerted by the retained material, called back fill, on the retaining wall is known as active earth pressure. As a result of the active pressure, the retaining wall tends to slide away from the retained earth.

2.61 Passive Earth Pressure

Sometimes, the retaining wall moves laterally against the retaining earth, which gets compressed. As a result of the movement of the retaining wall, the compressed earth is subjected to a pressure (which is in the opposite direction of the active pressure) known as passive earth pressure.

2.62 Rankine's Theory for Active Earth Pressure

According to Rankine's theory, the horizontal thrust (P) offered by the retaining wall on the retained material is given by

$$P = \frac{w.h^2}{2}\left(\frac{1-\sin\phi}{1+\sin\phi}\right)$$

where w = Specific weight of the retained material,

h = Height of retaining wall, and

ϕ = Angle of repose of the retained earth.

If the retained material is subjected to some superimposed or surcharged load (*i.e.* pressure due to traffic etc.), it will cause a constant pressure on the retaining wall from top to bottom. The total horizontal pressure (P) due to surcharged load is given by

$$P = p\left(\frac{1-\sin\phi}{1+\sin\phi}\right)$$

where p = Intensity of supercharged load.

2.63 Reinforced Cement Concrete Beam

The following assumptions are made in the theory of reinforced cement concrete.

1. All the tensile stresses are taken up by the steel reinforcement only.
2. There is a sufficient bond between the steel and concrete.
3. The modulus of elasticity for steel and concrete is constant.
4. The steel and concrete is stressed within elastic limit.

2.64 Critical and Actual Neutral Axis

The critical neutral axis of a section is based on the principle that the neutral axis is situated at the centre of gravity of a given section.

The actual neutral axis of a section is based on the principle that the moment of areas of compression and tension zones are equal.

Notes : 1. A beam is said to be *under-reinforced beam* when the amount of reinforcement is less than the proper requirement. In this case, the depth of actual neutral axis will be less than that of the critical neutral axis.

2. A beam is said to be *balanced beam* when the amount of reinforcement is equal to the proper requirement. In this case, the depth of actual neutral axis will be the same as that of critical neutral axis.

3. A beam is said to be *over-reinforced beam* when the amount of reinforcement is more than the proper requirement. In this case, the depth of actual neutral axis will be more than the critical neutral axis.

2.65 Mechanical Properties of Materials

In general, all the materials used by the engineers, may be classified, on the basis of their physical properties, into the following four types:

1. *Elastic materials.* When a material regains its original position, on the removal of the external force, it is called an elastic material.

2. *Plastic materials.* When a material does not regain its original position, on the removal of the external force, it is called a plastic material.

3. *Ductile materials.* When a material can undergo a considerable deformation without rupture (*e.g.* when a material can be drawn into wires), it is called a ductile material.

4. *Brittle materials.* When a material cannot undergo any deformation (like glass) and it fails by rupture, it is called a brittle material.

2.66 Stress-Strain Diagram for a Mild Steel Under Tensile Test

The stress-strain diagram for a mild steel specimen under tensile test is shown in Fig. 2.38. We see that from *O* to *A* is a straight line which represents that the stress is proportional to strain. It is thus obvious that Hooke's law holds good upto point *A*, which is called *elastic limit*. When the material is stressed beyond this limit (*i.e.* point *A*), the strain increases more quickly than the stress. The points *B* and *C* are called *upper yield point* and *lower yield point* respectively. The stress corresponding to point *D* is called the *ultimate stress*. After the specimen has reached the ultimate stress, a neck is formed which decreases the cross-sectional area of the specimen. A little consideration will show that the stress (or load) necessary to break away the specimen at point *E* is less than the ultimate stress. The stress corresponding to point *E* is called *breaking stress*.

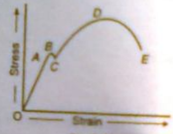


Fig. 2.38

It may be noted that

1. Ultimate stress $= \dfrac{\text{Ultimate load}}{\text{Original cross-sectional area}}$

2. Breaking stress $= \dfrac{\text{Breaking load}}{\text{Original cross-sectional area}}$

3. Percentage reduction in area $= \dfrac{\text{Original area} - \text{Final area}}{\text{Original area}} \times 100$

4. Percentage elongation $= \dfrac{\text{Final length} - \text{Original length}}{\text{Original length}} \times 100$

Notes : 1. The tensile test is performed on ductile materials and the compression test is performed on brittle materials.

2. The ratio of ultimate stress to the working stress is known as *factor of safety*. Its value is more than one.

OBJECTIVE TYPE QUESTIONS

1. Whenever some external system of forces acts on a body, it undergoes some deformation. As the body undergoes some deformation, it sets up some resistance to the deformation. This resistance per unit area to deformation, is called
   (*a*) strain (*b*) stress
   (*c*) pressure (*d*) modulus of elasticity

2. The unit of stress in S.I. units is
   (*a*) N/mm^2 (*b*) kN/mm^2 (*c*) N/m^2 (*d*) any one of these
3. The deformation per unit length is called
   (*a*) tensile stress (*b*) compressive stress
   (*c*) shear stress (*d*) strain
4. The unit of strain is
   (*a*) N-mm (*b*) N/mm (*c*) mm (*d*) no unit
5. Strain is equal to
   (*a*) $l/\delta l$ (*b*) $\delta l/l$ (*c*) $l.\delta l$ (*d*) $l+\delta l$
   where l = Original length, and δl = Change in length.
6. When a body is subjected to two equal and opposite pushes, as a result of which the body tends to reduce its length, the ress and strain induced is compressive.
   (*a*) True (*b*) False
7. When a body is subjected to two equal and opposite pulls, as a result of which the body tends to extend its length, the stress and strain induced is
   (*a*) compressive stress, tensile strain (*b*) tensile stress,compressive strain
   (*c*) tensile stress, tensile strain (*d*) compressive stress, compressive strain
8. When a body is subjected to two equal and opposite forces, acting tangentially across the resisting section, as a result of which the body tends to shear off across the section, the stress and strain induced is
   (*a*) tensile stress, tensile strain (*b*) compressive stress, compressive strain
   (*c*) shear stress, tensile strain (*d*) shear stress, shear strain
9. Which of the following is a proper sequence?
   (*a*) proportional limit, elastic limit, yielding, failure
   (*b*) elastic limit, proportional limit, yielding, failure
   (*c*) yielding, proportional limit, elastic limit, failure
   (*d*) none of the above
10. Hook's law holds good up to
    (*a*) yield point (*b*) elastic limit (*c*) plastic limit (*d*) breaking point
11. Whenever a material is loaded within elastic limit, stress is .... strain.
    (*a*) equal to (*b*) directly proportional to
    (*c*) inversely proportional to
12. The ratio of linear stress to the linear strain is called
    (*a*) modulus of rigidity (*b*) modulus of elasticity
    (*c*) bulk modulus (*d*) Poisson's ratio
13. The unit of modulus of elasticity is same as those of
    (*a*) stress, strain and pressure (*b*) stress, force and modulus of rigidity
    (*c*) strain, force and pressure (*d*) stress, pressure and modulus of rigidity

3

Hydraulics and Fluid Mechanics

3.1 Introduction

The word 'Hydraulics' has been derived from a Greek word 'Hudour' which means water. The subject 'Hydraulics' is that branch of Engineering - science which deals will water at rest or in motion. The subject 'Fluid Mechanics' is that branch of Engineering-science which deals with the behaviour of fluid under the conditions of rest and motion.

3.2 Important Terms Used in Hydraulics and Fluid Mechanics

The following are important terms used in Hydraulics and Fluid Mechanics :

1. *Density or mass density.* It is defined as the mass per unit volume of a liquid at a standard temperature and pressure. It is usually denoted by ρ (rho). It is expressed in kg/m^3. Mathematically, density or mass density,

$$\rho = m / V$$

where

m = Mass of the liquid, and

V = Volume of the liquid.

2. *Weight density or specific weight.* It is defined as the weight per unit volume of a liquid at a standard temperature and pressure. It is usually denoted by w. It is expressed in kN/m^3 or N/m^3 or N/mm^3. Mathematically, weight density or specific weight,

$$w = \rho . g$$

Note : For water, $w = 9.81\ kN/m^3 = 9.81 \times 10^3\ N/m^3 = 9.81 \times 10^{-6}\ N/mm^3$.

3. *Specific volume.* It is defined as the volume per unit mass of the liquid. It is denoted by v. Mathematically, specific volume,

$$v = V / m = 1/\rho$$

4. *Specific gravity.* It is defined as the ratio of specific weight of a liquid to the specific weight of pure water at a standard temperature (4° C). It has no units.

Note : The specific gravity of pure water is taken as unity.

3.3 Properties of Liquid

The following properties of liquid are important from the subject point of view :

1. *Viscosity.* It is also known as *absolute viscosity* or *dynamic viscosity*. It is defined as the property of a liquid which offers resistance to the movement of one layer of liquid over another adjacent layer of liquid. The viscocity of a liquid is due to cohesion and interaction between particles.

2. *Kinematic viscosity.* It is defined as the ratio of dynamic viscosity to the density of liquid.

3. *Compressibility.* It is that property of a liquid by virtue of which liquids undergo a change in volume with the change in pressure. The compressibility is the reciprocal of bulk moduls of elasticity, which is defined as the ratio of compressive stress to volumetric strain.

* Refer also Art. 3.41

4. *Surface tension.* It is that property of a liquid which enables it to resist tensile stress. It is denoted by σ (sigma). It is expressed in N/m.

5. *Capillarity.* It is defined as a phenomenon of rise or fall of a liquid surface in a small vertical tube held in a liquid relative to general level of the liquid. The height of rise or fall (h) in the tube is given by

$$h = \frac{4\sigma \cos\alpha}{wd}$$

where

σ = Surface tension,

α = Angle of contact of the liquid surface,

w = Specific weight of liquid, and

d = Diameter of the capillary tube.

3.4 Pressure of a Liquid

When a liquid is contained in a vessel, it exerts force at all points on the sides and bottom of the vessel. The force per unit area is called *intensity of pressure*. Mathematically, intensity of pressure,

$$p = P / A$$

where

P = Force acting on the liquid, and

A = Area on which the force acts.

The intensity of pressure at any point, in a liquid at rest is equal to the product of weight density of the liquid (w) and the *vertical height from the free surface of the liquid (h). Mathematically, intensity of pressure,

$$p = w . h$$

From this expression, we see that the intensity of pressure at any point, in a liquid, is directly proportional to depth of liquid from the surface.

The intensity of pressure may be expressed either in N/m^2, N/mm^2 or in metres of liquid or mm of liquid. It is also expressed in pascal (briefly written as Pa), such that

$$1 Pa = 1 N/m^2;\ 1 kPa = 1 kN/m^2 \text{ and } 1 MPa = 1 MN/m^2 = 1 N/mm^2$$

3.5 Pascal's Law

According to Pascal's law, the intensity of pressure at any point in a fluid at rest is same in all directions.

3.6 Atmospheric Pressure, Gauge Pressure and Absolute Pressure

The atmospheric air exerts a normal pressure upon all surfaces with which it is in contact and it is known as *atmospheric pressure*. It is also known as *barometric pressure*. The atmospheric pressure at sea level (above absolute zero) is called standard atmospheric pressure and its value is given as follows :

$$\text{Standard atmospheric pressure} = 101.3\ kN/m^2 \text{ or } kPa\ (1 kN/m^2 = 1 kPa)$$
$$= 10.3 \text{ m of water}$$
$$= 760 \text{ mm of Hg}$$

The pressure measured with the help of a pressure gauge is known as *gauge pressure*, in which atmospheric pressure is taken as datum. All the pressure gauges record the difference between the

* It is also known as static head.

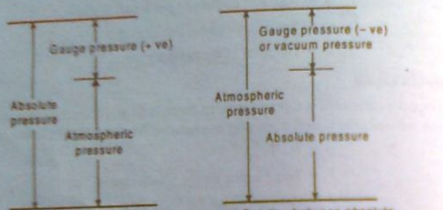
actual pressure and the atmospheric pressure. The actual pressure is known as *absolute pressure*. Mathematically

Absolute pressure = Atmospheric pressure + Gauge pressure (Positive)

This relation is used for pressures above atmospheric, *i.e.* for positive gauge pressure, as shown in Fig. 3.1 (*a*). For pressures below atmospheric, the gauge pressure will be negative. This negative gauge pressure is known as vacuum pressure. Therefore

Absolute pressure = Atmospheric pressure – Negative gauge pressure or vacuum pressure

This relation is shown in Fig 3.1 (*b*).



(a) Relation between absolute, atmospheric and gauge pressure.

(b) Relation between absolute, atmospheric and vacuum pressure.

Fig. 3.1

3.7 Measurement of Pressure

The pressure of a liquid may be measured by the manometers. These are the devices used for measuring the pressure at a point in a liquid by balancing the column of the liquid by the same or another column of liquid. The manometers are classified as follows:

1. Simple manometers such as piezometer and U-tube manometer.
2. Differential manometer.

A *Piezometer* is the simplest form of manometers used for measuring moderate pressures of liquids.

A *manometer* is used to measure

(*a*) High pressure of liquids,

(*b*) Vacuum pressures, and

(*c*) Pressure in pipes and channels.

A *differential manometer* is used to measure difference of pressures between two points in a pipe.

3.8 Total Pressure and Centre of Pressure

The total pressure is defined as the force exerted by a static fluid on a surface (either plane or curved) when the fluid comes in contact with the surface. This force is always normal to the surface.

The centre of pressure is defined as the point of application of the resultant pressure on the surface.

The total pressure and centre of pressure on the immersed surfaces are as follows :

1. *Horizontally immersed surface.* The total pressure on a horizontally immersed surface, as shown in Fig. 3.2, is given by

$$P = w A \bar{x}$$

where w = Specific weight of the liquid,

A = Area of the immersed surface, and

$\bar{x}$ = Depth of the centre of gravity of the immersed surface from the liquid surface.

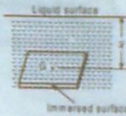


Fig. 3.2

The above expression holds good for all surfaces whether flat or curved.

2. *Vertically immersed surface.* The total pressure on a vertically immersed surface, as shown in Fig. 3.3, is given by

$$P = w A \bar{x}$$

and the depth of centre of pressure from the liquid surface,

$$\bar{h} = \frac{I_G}{A\bar{x}} + \bar{x}$$

where A = Area of immersed surface,

$\bar{x}$ = Depth of centre of gravity of the immersed surface from the liquid surface, and

I_G = Moment of inertia of immersed surface about the horizontal axis through its centre of gravity.

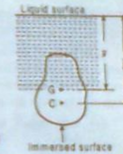


Fig. 3.3

3. *Inclined immersed surface.* The total pressure on an inclined surface, as shown in Fig. 3.4, is given by

$$P = w A \bar{x}$$

and the depth of centre of pressure from the liquid surface,

$$\bar{h} = \frac{I_G \sin^2\theta}{A\bar{x}} + \bar{x}$$

where θ = Angle at which the immersed surface is inclined with the liquid surface.

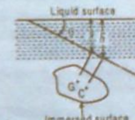


Fig. 3.4

4. *Curved immersed surface.* The total force on the curved surface, as shown in Fig. 3.5, is given by

$$P = \sqrt{(P_H)^2 + (P_V)^2}$$

and the direction of the resultant force on the curved surface with the horizontal is given by

$$\tan\theta = \frac{P_V}{P_H} \quad \text{or} \quad \theta = \tan^{-1}\left[\frac{P_V}{P_H}\right]$$

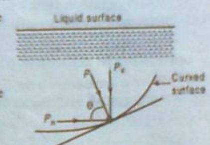


Fig. 3.5

where P_H = Horizontal force on the curved surface and is equal to the total pressure on the projected area of the curved surface on the vertical plane, and

P_V = Vertical force on the curved surface and is equal to the weight of the liquid supported by the curved surface upto the liquid surface.

3.9 Lock Gates

The lock gates are provided in navigation chambers to change the water level in a canal or river for navigation. There are two sets of gates, one set on either side of the chamber.

In a lock gate, the reaction between the two gates (R) is given by

$$R = \frac{P}{2 \sin \alpha}$$

where P = Resultant water pressure on the lock gate, and

α = Inclination of the gate with the normal to the side of the lock.

3.10 Buoyancy

When a body is immersed wholly or partially in a liquid, it is lifted up by a force equal to the weight of liquid displaced by the body. This statement is known as *Archimede's principle.*

The tendency of a liquid to uplift an immersed body, because of the upward thrust of the liquid, is known as *buoyancy*. The force tending to lift up the body is called the force of buoyancy or *buoyant force* and it is equal to the weight of the liquid displaced. The point through which the buoyant force is supposed to act, is known as *centre of buoyancy.* It may be noted that

(*a*) If the force of buoyancy is more than the weight of the liquid displaced, then the body will float.

(*b*) If the force of buoyancy is less than the weight of the liquid displaced, then the body will sink down.

3.11 Equilibrium of Floating Bodies

The equilibrium of floating bodies is of the following three types:

1. *Stable equilibrium.* If a body floating in a liquid returns back to its original position, when given a small angular displacement, then the body is said to be in stable equilibrium.

2. *Unstable equilibrium.* If a body floating in a liquid does not return back to its original position and heels farther away when given a small angular displacement, then the body is said to be in unstable equilibrium.

3. *Neutral equilibrium.* If a body floating in a liquid occupies a new position and remains at rest in this new position, when given a small angular displacement, then the body is said to be in neutral equilibrium.

3.12 Metacentre and Metacentric Height

The *metacentre* may be defined as a point about which a floating body starts oscillating, when given a small angular displacement. It is denoted by M.

The *metacentric height* is the distance between the centre of gravity (G) of the floating body and the metacentre (M). Mathematically, metacentric height,

$$GM = \frac{I}{V} - BG = BM - BG$$

where I = Moment of inertia of the sectional area of the floating body at the water surface.

V = Volume of the body submerged in water, and

BG = Distance between the centre of buoyancy (B) and the centre of gravity (G).

The conditions of equilibrium for a floating and submerged body are as follows :

S. No.	*Equilibrium condition*	*Floating body*	*Submerged body*
1.	Stable	M lies above G	B lies above G
2.	Unstable	M lies below G	B lies below G
3.	Neutral	M and G coincides	B and G coincides

The time of oscillation (T) of a floating body is given by

$$T = 2\pi \sqrt{\frac{k^2}{h.g}}$$

where k = Radius of gyration of the floating body about its centre of gravity, and

h = Metacentric height of the floating body = GM

3.13 Fluid Kinematics

The Fluid Kinematics is that branch of Fluid Mechanics which deals with the study of velocity and acceleration of the fluid particles without taking into consideration any force or energy.

3.14 Rate of Discharge

The quantity of liquid flowing per second through a section of a pipe or a channel is called *discharge* and is measured in cumecs (m^3/s). Mathematically, discharge,

$$Q = a\,v$$

where a = Cross-sectional area of the pipe, and

v = Average velocity of the liquid.

It may noted that

(*a*) The velocity of the liquid is maximum at the centre of a pipe and is minimum near the walls.

(*b*) $1\ m^3 = 1000$ litres.

3.15 Equation of Continuity

If an incompressible liquid is continuously flowing through a pipe or a channel (whose cross - sectional area may or may not be constant), the quantity of liquid passing per second is the same at all sections. This is known as *equation of continuity* of a liquid flow. Mathematically,

$$Q_1 = Q_2 = Q_3 = \ldots\ldots \quad \text{or} \quad a_1 v_1 = a_2 v_2 = a_3 v_3 = \ldots\ldots$$

3.16 Types of Flows in a Pipe

The type of flow of a liquid depends upon the manner in which the particles unite and move. Though there are many types of flows, yet the following are important from the subject of view :

1. *Uniform flow.* A flow, in which the liquid particles at all sections of a pipe or channel have the same velocities, is called a uniform flow.

2. *Non-uniform flow.* A flow, in which the liquid particles at different sections of a pipe or channel have different velocities, is called a non-uniform flow.

3. *Streamline flow.* A flow, in which each liquid particle has a definite path and the paths of individual particles do not cross each other, is called a stream line flow.

4. *Turbulent flow.* A flow, in which each liquid particle does not have a definite path and the paths of individual particles also cross each other, is called a turbulent flow.

5. *Steady flow.* A flow, in which the quantity of liquid flowing per second is constant, is called a steady flow. A steady flow may be uniform or non - uniform.

6. *Unsteady flow.* A flow, in which the quantity of liquid flowing per second is not constant, is called an unsteady flow.

7. *Compressible flow.* A flow, in which the volume of a fluid and its density changes during the flow, is called a compressible flow. All the gases are considered to have compressible flow.

8. *Incompressible flow.* A flow in which the volume of a fluid and its density does not change during the flow, is called an incompressible flow. All the liquids are considered to have incompressible flow.

9. *Rotational flow.* A flow, in which the fluid particles also rotate (*i.e.* have some angular velocity) about their own axes while flowing, is called a rotational flow.

10. *Irrotational flow.* A flow, in which the fluid particles do not rotate about their own axes and retain their orginal orientations, is called an irrotational flow.

11. *One-dimensional flow.* A flow, in which the streamlines of its moving particles are represented by straight line, is called an one-dimensional flow.

12. *Two-dimensional flow.* A flow, whose stream lines of its moving particles are represented by a curve, is called a two-dimensional flow.

13. *Three - dimensional flow.* A flow, whose streamlines are represented in space *i.e.* along the three mutually perpendicular directions, is called a three - dimensional flow.

3.17 Dynamics of Fluid

The dynamics of fluid flow is defined as that branch of science which deals with the study of fluids in motion considering the forces which cause the flow.

3.18 Different Types of Energies or Head of a Liquid in Motion

The following are the three types of energies or head of flowing liquids:

1. *Potential energy or potential head.* It is due to the position above some suitable datum line. It is denoted by z.

2. *Kinetic energy or kinetic (or velocity) head.* It is due to the velocity of flowing liquid. Its value is given by $v^2 / 2g$, where v is the velocity of flow and g is the acceleration due to gravity.

3. *Pressure energy or pressure head.* It is due to the pressure of liquid. Its value is given by p / w, where p is the pressure in N / m² and w is the weight density of the liquid in N / m³.

Note: The total energy or total head of a liquid particle in motion is given as follows :

Total energy, E = Potential energy + Kinetic energy + Pressure energy

and total head, H = Potential head + Kinetic head + Pressure head

3.19 Bernoulli's Equation

The Bernoulli's equation states that "For a perfect incompressible liquid, flowing in a continuous stream, the total energy of a particle remains the same, while the particle moves from one point to another. Mathematically,

$$z_1 + \frac{v_1^2}{2g} + \frac{p_1}{w} = z_2 + \frac{v_2^2}{2g} + \frac{p_2}{w} = \text{Constant}$$

The Bernoulli's equation is applied to venturimeter, orifice meter and pitot tube.

The Bernoulli's equation for real fluids is given by

$$\frac{p_1}{w} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{w} + \frac{v_2^2}{2g} + z_2 + h_L$$

where h_L = Loss of energy between sections 1 and 2.

3.20 Euler's Equation

The Euler's equation in the differential form for the motion of liquids is given as follows :

$$\frac{dp}{\rho} + g.dz + v.dv = 0$$

This equation is based on the following assumptions :

(*a*) The fluid is non - viscous.

(*b*) The fluid is homogeneous and incompressible.

(*c*) The flow is continuous, steady and along the streamline.

(*d*) The velocity of flow is uniform over the section.

Note: The Bernoulli's equation is obtained by integrating the above Euler's equation.

3.21 Venturimeter

It is an instrument used to measure the discharge of liquid flowing in a pipe. It consists of three parts, *i.e.*, the converging cone, the throat and the diverging cone. The length of the divergent cone is made about three to four times longer than that of the divergent cone in order to avoid tendency of breaking away the stream of liquid and to minimise frictional losses. It may be noted that

(*a*) The velocity of liquid at the throat is higher than that of inlet.

(*b*) The pressure of liquid at the throat is lower than that of inlet.

(*c*) The velocity and pressure of liquid flowing through the divergent portion decreases.

The discharge through a venturimeter is given by

$$Q = \frac{C_d\, a_1\, a_2}{\sqrt{a_1^2 - a_2^2}} \sqrt{2gh}$$

where C_d = Coefficient of discharge,

a_1 = Area at inlet,

a_2 = Area at throat, and

h = Venturi-head.

3.22 Orifice Meter and Pitot Tube

The orifice meter is a device (cheaper than venturimeter) used for measuring the discharge of the liquid flowing through a pipe. It works on the same principle as that of venturimeter.

The pitot tube is a small open tube bent at right angle. It is used to measure the velocity of flow at the required point in a pipe. It is determined by measuring the rise of liquid in a tube.

3.23 Momentum Equation

The momentum equation is based on the law of momentum or momentum principle which states that "*The net force acting on a mass of fluid is equal to the change in momentum of flow per unit time in that direction*." Mathematically, force acting on the fluid,

$$F = \frac{d\,(mv)}{dt}$$

where mv = Momentum.

The impulse - momentum equation is given by

$$F \times dt = d\,(mv)$$

It states that 'the impulse of a force (F) acting on a fluid mass (m) in a short interval of time (dt) is equal to the change of momentum [$d\,(mv)$] in the direction of force.

3.24 Orifice

The *orifice* is a small opening in the wall or base of a vessel through which the fluid flows. A *mouthpiece* is an attachment in the form of a small tube or pipe fixed to the orifice. It length is usually two to three times the diameter of orifice. It is used to increase the amount of dicharge.

3.25 Hydraulic Coefficients

The following are the hydraulic coefficients :

1. *Coefficient of contraction* (C_c). It is defined as the ratio of area of jet at *vena contracta (a_c) to the area of orifice (a).

2. *Coefficient of velocity* (C_v). It is defined as the ratio of the actual velocity of the jet at vena contracta (v) to the theoretical velocity (v_{th}).

3. *Coefficient of discharge* (C_d). It is defined as the ratio of the actual discharge through the orifice (Q) to the theoretical discharge (Q_{th}). The coefficient of discharge is equal to the product of C_c and C_v.

4. *Coefficient of resistance* (C_r). It is defined as the ratio of loss of head in the orifice to the head of water available at the exit of the orifice.

Note: The coefficient of velocity is determined experimentally by using the following relation, *i.e.*

$$C_v = \sqrt{\frac{x^2}{4yH}}$$

where
x = Horizontal distance,
y = Vertical distance, and
H = Constant water head.

3.26 Important Expressions used in Orifices and Mouthpieces

The following are the important expressions used in orifices and mouthpieces :

(*a*) Discharge through a large rectangular orifice,

$$Q = \frac{2}{3} C_d . b \sqrt{2g}\left[H_2^{3/2} - H_1^{3/2}\right]$$

---

* The point at which the streamlines first become parallel is called *vena contracta*. The cross-sectional area of the jet at vena contrata is less than that of the orifice. The theoretical velocity of jet at vena contracta (v_a) is given by

$$v_a = \sqrt{2gH}$$

This expression is called *Torricelli's theorem*.

where
C_d = Coefficient of discharge,
b = Breadth of the orifice,
H_1 = Height of the liquid above the top of the orifice, and
H_2 = Height of the liquid above the bottom of the orifice.

(*b*) Discharge through a wholly submerged orifice,

$$Q = C_d . b(H_2 - H_1)\sqrt{2gH}$$

where
H_1 = Height of water (on the upstream side) above the top of the orifice,
H_2 = Height of water (on the downstream side) above the bottom of the orifice, and
H = Difference between two water levels on either side of the orifice.

(*c*) Time required to empty the tank completely through an orifice at the bottom,

$$T = \frac{2A\sqrt{H_1}}{C_d . a\sqrt{2g}}$$

(*d*) Time required to empty the hemispherical tank through an orifice at the bottom,

$$T = \frac{14\pi R^{5/2}}{15 C_d . a\sqrt{2g}}$$

where R = Radius of hemispherical tank.

(*e*) Discharge through an external mouthpiece,

$$Q = 0.855\, a\sqrt{2gH}$$

where
a = Cross-sectional area of the mouthpiece, and
H = Height of liquid above the mouthpiece.

(*f*) Discharge through the internal mouthpiece when it is running free,

$$Q = 0.5a\sqrt{2gH}$$

(*g*) Discharge through the internal mouthpiece when it is running full,

$$Q = 0.707a\sqrt{2gH}$$

Notes: 1. The re-entrant or Borda's mouthpiece is an internal mouthpiece.

2. If the jet of liquid after contraction does not touch the sides of the mouthpieces, then the mouth piece is said to be running free. In this case, the length of mouthpiece is equal to diameter of the orifice.

3. If the jet of liquid after contraction expands and fills up the whole mouthpiece, then the mouthpiece is said to be running full. In this case, the length of mouthpiece is more than three times the diameter of orifice.

3.27 Notches and Weirs

A *notch* may be defined as an opening provided in the side of a tank or vessel such that the liquid surface in the tank is below the top edge of the opening. It is generally made of a metallic plate. It is used for measuring the rate of flow of a liquid through a small channel or a tank.

A *weir* may be defined as any regular obstruction in an open channel over which the flow takes place. It is made of masonry or concrete. It is used for measuring the rate of flow of water in rivers or streams.

3.28 Important Expressions used in Notches and Weirs

The following are the important expressions used in notches and weirs.

(*a*) Discharge over a rectangular notch or weir,

$$Q = \frac{2}{3} C_d . b \sqrt{2g} . H^{3/2}$$

where b = Width of notch or weir, and

H = Height of liquid above the sill of the notch.

(*b*) Discharge over a triangular notch or weir,

$$Q = \frac{8}{15} C_d \sqrt{2g} . \tan\left(\frac{\theta}{2}\right) H^{5/2}$$

For a right angled V-notch, $\theta = 90°$.

(*c*) Discharge over a trapezoidal notch or weir (also called Cippoletti weir) is equal to the sum of discharge over a rectangular notch or weir and the discharge over a triangular notch or weir.

(*d*) Discharge over a rectangular weir, according to Francis formula is given by

$$Q = \frac{2}{3} C_d \; (L - 0.1 n H) \sqrt{2g} \; H^{3/2}$$

where n = Number of end contractions.

(*e*) Maximum discharge over a broad crested weir,

$$Q_{max} = 1.71 \, C_d . L . H^{3/2}$$

Notes : 1. A weir is said to be a *broad crested weir*, if the width of the crest of the weir is more than half the height of water above the weir crest.

2. A weir is said to be a *narrow crested weir*, if the width of the crest of the weir is less than half the height of water above the weir crest.

3. When the water level on the downstream side of a weir is above the top surface of a weir, then the weir is known as *submerged* or *drowned weir*.

4. A weir, generally, used as a spillway of a dam is *Ogee weir*.

5. It has been observed that whenever water is flowing over a rectangular weir, having no end contractions, the nappe (*i.e.*, the sheet of water flowing over the weir) touches the side walls of the channel. After flowing over the weir, the nappe falls away from the weir, thus creating a space beneath the water. In such a case, some air is trapped beneath the weir.

6. If the atmospheric pressure exists beneath the nappe, it is then known as *free nappe*.

7. If the pressure below the nappe is negative, it is then called a *depressed nappe*.

8. Sometimes, no air is left below the water and the nappe adheres or clings to the downstream side of the weir. Such a nappe is called *clinging nappe* or an *adhering nappe*.

3.29 Pipes and Channels

A pipe is a closed conduit (generally of circular section) which is used for carrying fluids under pressure. The fluid completely fills the cross-section of the pipe. When the pipe is partially full of liquid, it then behaves like an *open channel*.

3.30 Loss of Head due to Friction in Pipe

According to Darcy's formula, the loss of head due to friction in the pipe (h_f) is given by

$$h_f = \frac{4 f l v^2}{2g . d}$$

where f = Darcy's coefficient,

l = Length of pipe,

v = Mean velocity of liquid in pipe, and

d = Diameter of pipe.

The major loss of head or energy is due to friction. The minor loss of head includes the following cases :

(*a*) Loss of head due to sudden enlargement,

$$h_e = \frac{(v_1 - v_2)^2}{2g}$$

(*b*) Loss of head due to sudden contraction,

$$h_c = \frac{v_2^2}{2g}\left[\frac{1}{C_c} - 1\right]^2$$

where C_c = Coefficient of contraction.

(*c*) Loss of head at the inlet of a pipe,

$$h_i = 0.5 \times \frac{v^2}{2g}$$

(*d*) Loss of head at the outlet of a pipe,

$$h_o = \frac{v^2}{2g}$$

3.31 Hydraulic Gradient and Total Energy Lines

The line representing the sum of pressure head (p/w) and potential head or datum head (z) with respect to some reference line is hydraulic gradient line (H.G.L.).

The line representing the sum of pressure head (p/w), datum head (z) and velocity head ($v^2/2g$) with respect to some reference line is known as total energy line (T.G.L.).

3.32 Pipes in Series or Compound Pipes

Figure 3.6 shows a system of pipes in series.

The difference of water level in the two tanks A and B is given by

$$H = \frac{4 f_1 l_1 v_1^2}{2g d_1} + \frac{4 f_2 l_2 v_2^2}{2g d_2} + \frac{4 f_3 l_3 v_3^2}{2g d_3}$$

If $f_1 = f_2 = f_3 = f$, then

$$H = \frac{4f}{2g}\left[\frac{l_1 v_1^2}{d_1} + \frac{l_2 v_2^2}{d_2} + \frac{l_3 v_3^2}{d_3}\right]$$

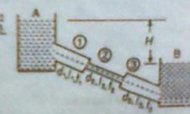


Fig. 3.6

If a compound pipe is to be replaced by a pipe of uniform diameter (known as equivalent pipe), then the loss of head and discharge of both the pipes should be same. The uniform diameter (d) of the equivalent pipe may be obtained from the following relation:

$$\frac{l}{d^5} = \frac{l_1}{d_1^5} + \frac{l_2}{d_2^5} + \frac{l_3}{d_3^5}$$

where $\quad l$ = Length of the equivalent pipe $= l_1 + l_2 + l_3$

3.33 Pipes in Parallel

Figure 3.7 shows a system of pipes in parallel. In such a case

(a) The rate of discharge in the main pipe is equal to the sum of discharges in each of the parallel pipes, *i.e.*

$$Q = Q_1 + Q_2$$

(b) The loss of head in each pipe is same, *i.e.*

$$h_{f1} = h_{f2} \text{ or } \frac{4 f_1 l_1 v_1^2}{2 g d_1} = \frac{4 f_2 l_2 v_2^2}{2 g d_2}$$

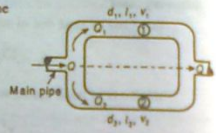


Fig. 3.7

3.34 Syphon

A syphon is a long bent pipe used to connect two reservoirs at different levels intervened by a high ridge. The highest point of the syphon is called the *summit*. An air vessel is provided at the summit in order to avoid interruption in the flow.

3.35 Power Transmitted through the Pipe

The power transmitted (in watts) through the pipe

= Weight of water flowing in N / s × Head of water in m

The power transmitted will be maximum when the head lost in friction is equal to one-third of the total supply head.

The maximum efficiency of transmission through a pipe is 66.67 percent.

3.36 Flow through Nozzle at the end of a Pipe

A nozzle is a tapering mouthpiece which is fitted to the end of a water pipe line to discharge water at a high velocity. A nozzle is generally made of convergent shape. The power transmitted through the nozzle is maximum when the head lost due to friction in the pipe is one-third of the total supply head at the inlet of the pipe. The diameter of the nozzle (d) for maximum transmission of power is given by

$$d = \left[\frac{D^5}{8 f l}\right]^{1/4}$$

where $\quad D$ = Diameter of pipe,

f = Darcy's coefficient of friction for pipe, and

l = Length of pipe.

3.37 Water Hammer

When a liquid flowing through a long pipe is suddenly brought to rest by closing the valve at the end of a pipe, then a pressure wave of high intensity is produced behind the valve. This pressure wave of high intensity has the effect of hammering action on the walls of the pipe. This phenomenon is known as *water hammer* or *hammer blow*.

The magnitude of water hammer depends upon

(a) The length of pipe line,

(b) The elastic properties of the pipe material,

(c) The elastic properties of the liquid flowing through the pipe, and

(d) The speed at which the valve is closed.

3.38 Flow Through Open Channels

According to Chezy formula, the mean velocity of liquid,

$$v = C\sqrt{m.i}$$

and discharge, $\quad Q = A.v = AC\sqrt{m.i}$

where $\quad C$ = Chezy's constant,

A = Area of flow,

m = Hydraulic mean depth $= \dfrac{\text{Area of flow } (A)}{\text{Wetted perimeter } (P)}$,

$= d/4$, for circular pipe

$i = \dfrac{h_f}{l}$ = Loss of head per unit length of pipe.

According to Manning's formula, discharge through an open channel,

$$Q = A.M m^{2/3} i^{1/2}$$

where $\quad M$ = Manning's constant.

3.39 Most Economical Section of a Channel

A channel is said to be most economical if

(a) It gives maximum discharge for a given cross-sectional area and bed shape,

(b) It has minimum wetted perimeter, and

(c) It involves lesser excavation for the designed amount of discharge.

The following points are worthnoting :

1. The most economical section of a rectangular channel is one which has hydraulic radius equal to half the depth of flow.

2. The most economical section of a trapezoidal channel is one which has hydraulic mean depth equal to half the depth of flow.

3. The most economical section of a triangular channel is one which has its sloping sides at an angle of 45° with the vertical.

4. The discharge through a channel of rectangular section is maximum when its breadth is twice the depth.

5. The discharge through a channel of trapezoidal section is maximum when the sloping side is equal to half the width at the top.

6. The discharge through a channel of circular section is maximum when the depth of water is equal to 0.95 times the diameter of the circular channel.

7. The velocity through a channel of circular section is maximum when the depth of water is equal to 0.81 times the diameter of circular channel.

8. The depth of water in a channel corresponding to the minimum specific energy is known as *critical depth*.

9. If the depth of water in an open channel is less than the critical depth, then the flow is known as *torrential flow*.

10. If the depth of water in an open channel is greater than the critical depth, then the flow is called *tranquil flow*.

3.40 Vortex Flow

When a cylindrical vessel, containing some liquid, is rotated about its vertical axis, the liquid surface is depressed down at the axis of its rotation and rises up near the walls of the vessel on all sides. This type of flow is known as *vortex flow*. It is of the following two types:

1. *Forced vortex flow*. In this type of flow, the vessel containing the liquid is forced to rotate about the fixed vertical axis with the help of some external torque.

2. *Free vortex flow*. In this type of flow, the liquid particles describe circular paths about a fixed vertical axis, without any external torque acting on the particles. The flow of water through the hole in the bottom of a wash basin is an example of free vortex flow.

The following important points may be noted for vortex flow :

(*a*) When a cylindrical vessel containing liquid is revolved, the surface of the liquid takes the shape of a paraboloid.

(*b*) The rise of liquid along the walls of a revolving cylinder about the initial level is same as the depression of the liquid at the axis of rotation.

(*c*) The total pressure on the bottom of a closed cylindrical vessel completely filled up with a liquid is equal to the sum of the total centrifugal pressure and the weight of the liquid in the vessel.

(*d*) The total pressure (P) on the top of a closed cylindrical vessel of radius (r) completely filled up with a liquid of specific weight (w) and rotating at ω rad / s about its vertical axis is given by

$$P = \frac{\pi w \omega^2 r^2}{4g}$$

(*e*) The increase in pressure at the outer edge of a drum of radius (r) completely filled up with liquid of mass density (ρ) and rotating at ω rad / s is $\dfrac{\rho\omega^2 r^2}{2}$.

(*f*) The tangential velocity (v) of the water element having a free vortex is inversely proportional to its distance from the centre.

3.41 Viscous Flow

We have already discussed in Art. 3.3 that viscosity (also called absolute or dynamic viscosity) is the property of a liquid which offers resistance to the movement of one layer of liquid over another adjacent layer of liquid. In other words, viscosity is the property of a liquid which controls its rate of flow. The viscosity of a liquid is due to cohesion and interaction between particles.

In S. I. units, the unit of viscosity is $N\text{-}s/m^2$ and in C. G. S. units, it is expressed in poise, such that

$$1 \text{ poise} = 0.1 \text{ N-s/m}^2$$

We have also discussed in Art. 3.3 that the ratio of dynamic viscosity to the density of the liquid is called *kinematic viscosity*. In S. I. units, the unit of kinematic viscosity is m^2/s and in C. G. S. units, it is expressed in stoke, such that

$$1 \text{ stoke} = 1 \text{ cm}^2/\text{s} = 10^{-4} \text{ m}^2/\text{s}$$

3.42 Newton's Law of Viscosity

According to Newton's law of viscosity, the shear stress on a layer of a fluid is directly proportional to the rate of shear strain.

The following important points may be noted for viscous flow :

(*a*) A fluid which has no viscosity is known as an *ideal fluid*.

(*b*) A fluid which has a viscosity is known as a *real fluid*.

(*c*) A fluid whose viscosity does not change with the rate of deformation or shear strain is known as *Newtonian fluid*.

(*d*) A fluid whose viscosity changes with the rate of deformation or shear strain is known as *Non - Newtonian fluid*.

(*e*) A flow in which the viscosity of fluid is dominating over the inertia forces, is called *laminar flow*. It takes place at very low velocities.

(*f*) A flow in which the inertia force is dominating over the viscosity, is called *turbulent flow*. It takes place at high velocities.

(*g*) The velocity at which the flow changes from the laminar flow to the turbulent flow, is called *critical velocity*. It is of two types, *i.e.*, lower critical velocity and higher critical velocity. The velocity at which the laminar flow stops, is known as *lower critical velocity*, while the velocity at which the turbulent flow starts, is known as *higher critical velocity*.

(*h*) The ratio of the inertia force to the viscous force is called *Reynold's number*. The flow in a pipe is laminar when Reynold's number is less than 2000 and flow is turbulent when Reynold's number is more than 2800. But when Reynold's number is between 2000 and 2800, the flow is neither laminar nor turbulent.

(*i*) The velocity corresponding to Reynold's number of 2000, is called lower critical velocity and the velocity corresponding to Reynold's number of 2800, is called higher critical velocity.

(*j*) The loss of head due to viscosity for laminar flow in pipe is

$$H_L = \frac{32 \mu v l}{w d^2}$$

where
μ = Viscosity of the liquid,
v = Velocity of the liquid in the pipe,
l = Length of pipe,
d = Diameter of pipe, and
w = Specific weight of flowing liquid.

(*k*) The loss of head due to friction in a pipe of uniform diameter in which a viscous flow is taking place is $16 / R_N$, where R_N is Reynold's number.

3.43 Viscous Resistance

Though the theory of viscosity has a number of applications, yet the viscous resistance on bearings is important. The following points may be noted for viscous resistance:

(*a*) Torque required to overcome viscous resistance of footstep bearing is

$$T = \frac{\pi^2 \mu N R^4}{60 t}$$

where μ = Viscosity of the oil,

N = Speed of the shaft,

R = Radius of the shaft, and

t = Thickness of the oil film.

(*b*) Torque required to overcome viscous resistance of a collar bearing is

$$T = \frac{\pi^2 \mu N}{60t}\left[(R_1)^4 - (R_2)^4\right]$$

where R_1 and R_2 = External and internal radius of collar.

(*c*) The coefficient of viscosity may be found out, experimentally, by the following methods:

(*i*) Capillary tube method; (*ii*) Orifice type viscometer;

(*iii*) Rotating cylinder method; and (*iv*) Falling sphere method.

(*d*) The coefficient of viscosity (in poises), according to the method of orifice type viscometer, is

$$\mu = \left[0.0022\, t - \frac{1.8}{t}\right] \times \text{Sp.gr. of liquid}$$

3.44 Compressible Flow of Fluids

We have already discussed that for an incompressible fluid flow, the total quantity of flow at different sections of a pipe is same, *i.e.*

$$Q = a_1 v_1 = a_2 v_2 = a_3 v_3 = ...$$

But in a compressible fluid flow, the mass of fluid flowing through any section of the pipe is same, *i.e.*,

$$m_1 = m_2 = m_3 = ...$$

$$\therefore \quad a_1 v_1 \rho_1 = a_2 v_2 \rho_2 = a_3 v_3 \rho_3 = ...$$

or

$$a_1 v_1 w_1 = a_2 v_2 w_2 = a_3 v_3 w_3 = ... \quad ...(\because w = \rho . g)$$

3.45 Velocity of Sound Wave

The velocity of sound in a fluid is given by

$$C = \sqrt{K / \rho}$$

where K = Bulk modulus, and

ρ = Density of the fluid.

3.46 Mach Number and its Importance

The ratio of velocity of fluid, in an undisturbed stream, to the velocity of sound wave, is known as *Mach number*. It gives us an important information about the type of flow. In general, the flow of a fluid is divided into the following four types depending upon the Mach number.

(*a*) When the Mach number is less than unity, the flow is called a ***sub-sonic flow***.

(*b*) When the Mach number is equal to unity, the flow is called a ***sonic flow***.

(*c*) When the Mach number is between 1 and 6, the flow is called a ***supersonic flow***.

(*d*) When the Mach number is more than 6, the flow is called ***hypersonic flow***.

3.47 Stagnation Point

A point in the flow, where the velocity of fluid is zero, is called a stagnation point.

3.48 Flow Around Immersed Bodies

We see that when a solid body is held in the path of a moving fluid and is completely immersed in it, the body will be subjected to some pressure or force. Conversely, if a body is moved with a uniform velocity through a fluid at rest, it offers some resistance to the moving body or the body has to exert some force to maintain its steady movement.

According to *Newton's law of resistance*, the force exerted by a moving fluid on an immersed body is directly proportional to the rate of change of momentum due to the presence of the body.

The following points may be noted for the flow around immersed bodies:

(*a*) Whenever a plate is held immersed at some angle with the direction of the flow of the liquid, it is subjected to some pressure. The component of this pressure, in the direction of the flow of the liquid, is known as *drag* and the component of this pressure at right angles to the direction of the flow of the liquid is known as *lift*.

(*b*) According to Prandtl – Blassius relation, the thickness of boundary layer in laminar flow is

$$\delta_{lam} = \frac{5x}{\sqrt{R_{NX}}}$$

and thickness of boundary layer in a turbulent flow,

$$\delta_{tur} = \frac{0.377x}{(R_{NX})^{1/5}}$$

where x = Distance between the leading edge of the body and the section where thickness of boundary layer is required, and

R_{NX} = Reynold's number at a distance x from the leading edge.

3.49 Types of Forces Present in a Moving Liquid

The important forces present in a moving liquid are as follows :

(*a*) *Inertia force*. It is the product of mass and acceleration of the flowing liquid.

(*b*) *Viscous force*. It is the product of shear stress due to viscosity and the cross-sectional area of flow.

(*c*) *Gravity force*. It is the product of mass and acceleration due to gravity of a flowing liquid.

(*d*) *Surface tension force*. It is the product of surface tension per unit length and length of the surface of flowing liquid.

(*e*) *Pressure force*. It is the product of intensity of pressure and the area of a flowing liquid.

(*f*) *Elastic force*. It is the product of elastic stress and the area of a flowing liquid.

3.50 Dimensionless Numbers

The important dimensionless numbers are as follows :

(*a*) *Reynold's number*. It is the ratio of the inertia force to the viscous force.

(*b*) *Froude's number*. It is the ratio of the inertia force to the gravity force.

(*c*) *Weber's number*. It is the ratio of the inertia force to the surface tension force.

(*d*) *Euler's number*. It is the ratio of the inertia force to the pressure force.

(*e*) *Mach's number or Cauchy's number*. It is the ratio of the inertia force to the elastic force.

OBJECTIVE TYPE QUESTIONS

1. The mass per unit volume of a liquid at a standard temperature and pressure is called
   (a) specific weight (b) mass density (c) specific gravity (d) none of these
2. The volume per unit mass of a liquid is called specific volume.
   (a) Yes (b) No
3. The weight per unit volume of a liquid at a standard temperature and pressure is called
   (a) specific weight (b) mass density (c) specific gravity (d) none of these
4. The specific weight of water in S.I. units is taken as
   (a) 9.81 kN/m^3 (b) 9.81×10^3 N/m^3 (c) 9.81×10^{-6} N/mm^3 (d) any one of these
5. The ratio of specific weight of a liquid to the specific weight of pure water at a standard temperature is called
   (a) density of liquid (b) specific gravity of liquid
   (c) compressibility of liquid (d) surface tension of liquid
6. The specific gravity has no units.
   (a) Agree (b) Disagree
7. The specific gravity of water is taken as
   (a) 0.001 (b) 0.01 (c) 0.1 (d) 1
8. The specific weight of sea water is .... that of pure water.
   (a) same as (b) less than (c) more than
9. The density of a liquid in kg/m^3 is numerically equal to its specific gravity.
   (a) True (b) False
10. The specific weight is also known as weight density.
    (a) Correct (b) Incorrect
11. The mass of 2.5 m^3 of a certain liquid is 2 tonnes. Its mass density is
    (a) 200 kg/m^3 (b) 400 kg/m^3 (c) 600 kg/m^3 (d) 800 kg/m^3
12. The specific gravity of an oil whose specific weight is 7.85 kN/m^3, is
    (a) 0.8 (b) 1 (c) 1.2 (d) 1.6
13. A vessel of 4 m^3 contains an oil which weighs 30 kN. The specific weight of the oil is
    (a) 4.5 kN/m^3 (b) 6 kN/m^3 (c) 7.5 kN/m^3 (d) 10 kN/m^3
14. The property of a liquid which offers resistance to the movement of one layer of liquid over another adjacent layer of liquid, is called
    (a) surface tension (b) compressibility (c) capillarity (d) viscosity
15. Kinematic viscosity is the product of dynamic viscosity and the density of the liquid.
    (a) Yes (b) No
16. The force per unit length is the unit of
    (a) surface tension (b) compressibility (c) capillarity (d) viscosity
17. The variation in the volume of a liquid with the variation of pressure is called its
    (a) surface tension (b) compressibility (c) capillarity (d) viscosity

18. The property of a liquid which enables it to resist tensile stress is called its surface tension.
    (a) Agree (b) Disagree
19. When a tube of smaller diameter is dipped in water, the water rises in the tube due to viscosity of water.
    (a) True (b) False
20. When a tube of smaller diameter is dipped in water, the water rises in the tube with an upward .... surface.
    (a) concave (b) convex
21. A glass tube of smaller diameter is used while performing an experiment for the capillary rise of water because
    (a) it is easier to see through the glass tube
    (b) glass tube is cheaper than a metallic tube
    (c) it is not possible to conduct this experiment with any other tube
    (d) all of the above
22. The mercuty does not wet the glass. This is due to the property of the liquid known as
    (a) cohesion (b) adhesion (c) viscosity (d) surface tension
23. With an increase in size of tube, the rise or depression of liquid in the tube due to surface tension will
    (a) decrease (b) increase
    (c) remain unchanged (d) depend upon the characteristics of liquid
24. A glass tube of small diameter (d) is dipped in fluid. The height of rise or fall in the tube is given by
    (a) $\frac{4wd}{\sigma \cos \alpha}$ (b) $\frac{\sigma \cos \alpha}{4wd}$ (c) $\frac{4\sigma \cos \alpha}{wd}$ (d) $\frac{wd}{4\sigma \cos \alpha}$
    where w = Specific weight of liquid,
    α = Angle of contact of the liquid surface, and
    σ = Surface tension.
25. In the manufacturing of lead shots, the property of surface tension is utilised.
    (a) Agree (b) Disagree
26. The surface tension of mercury at normal temperature is .... that of water.
    (a) same as (b) lower than (c) higher than
27. The unit of surface tension is
    (a) N/m (b) N/m^2 (c) N/m^3 (d) N-m
28. The viscosity of a liquid is due to cohesion of its particles.
    (a) Correct (b) Incorrect
29. The viscosity of a liquid .... its rate of flow through a hole in a vessel.
    (a) effects (b) does not effect
30. The viscosity of water is .... than that of mercury.
    (a) higher (b) lower

258. (*c*)	259. (*c*)	260. (*d*)	261. (*b*)	262. (*c*)	263. (*b*)
264. (*b*)	265. (*d*)	266. (*b*)	267. (*a*)	268. (*c*)	269. (*a*)
270. (*d*)	271. (*c*)	272. (*d*)	273. (*b*)	274. (*a*)	275. (*b*)
276. (*c*)	277. (*d*)	278. (*b*)	279. (*c*)	280. (*d*)	281. (*a*)
282. (*c*)	283. (*a*)	284. (*a*)	285. (*a*)	286. (*b*)	287. (*d*)
288. (*c*)	289. (*a*)	290. (*a*)	291. (*b*)	292. (*c*)	293. (*a*)
294. (*c*)	295. (*c*)	296. (*c*)	297. (*b*)	298. (*b*)	299. (*c*)
300. (*a*)	301. (*a*)	302. (*b*)	303. (*b*)	304. (*b*)	305. (*b*)
306. (*b*)	307. (*a*)	308 (*a*)	309. (*a*)	310. (*a*)	311. (*c*)
312. (*c*)	313. (*d*)	314. (*a*)	315. (*c*)	316. (*b*)	317. (*c*)
318. (*a*)	319. (*c*)	320. (*c*)	321. (*a*)	322. (*a*)	323. (*a*)
324. (*b*)	325. (*c*)	326. (*d*)	327. (*a*)	328. (*a*)	329. (*a*)
330. (*d*)	331. (*b*)	332. (*a*)	333. (*b*)	334. (*a*)	335. (*c*)
336. (*b*)	337. (*c*)	338. (*d*)	339. (*d*)	340. (*c*)	341. (*a*)
342. (*c*)	343. (*a*)	344. (*c*)	345. (*a*)	346. (*b*)	347. (*a*)
348. (*d*)	349. (*b*)	350. (*d*)	351. (*a*)	352. (*d*)	353. (*d*)
354. (*b*)	355. (*c*)	356. (*c*)	357. (*b*)	358. (*a*)	359. (*b*)
360. (*b*)	361. (*a*)	362. (*a*)	363. (*a*)	364. (*d*)	365. (*d*)
366. (*a*)	367. (*a*)	368. (*c*)	369. (*d*)	370. (*c*)	371. (*b*)
372. (*a*)	373. (*d*)	374. (*d*)	375. (*b*)	376. (*a*)	377. (*a*)
378. (*c*)	379. (*a*)	380. (*d*)	381. (*a*)	382. (*c*)	383. (*b*)
384. (*a*)	385. (*a*)	386. (*a*)	387. (*a*)	388. (*a*)	389. (*d*)
390. (*c*)	391. (*d*)	392: (*a*)	393. (*a*)	394. (*d*)	395. (*c*)

4

Hydraulic Machines

4.1 Introduction

The subject '*Hydraulic Machines*' may be defined as that branch of Engineering - science which deals with the machines run by water under some head or raising the water to higher levels.

4.2 Impact of Jets

The following relations are important :

(*a*) Force exerted by a jet of water impinging normally on a fixed plate,

$$*F_X = \frac{waV^2}{g} \text{ (in newton)}$$

where w = Specific weight of water in N / m³,

a = Cross-sectional area of jet in m², and

V = Velocity of jet in m / s.

(*b*) Force exerted by a jet of water impinging normally on a fixed plate inclined at an angle θ with the jet,

$$F_X = \frac{waV^2}{g} \times \sin^2\theta \text{ (in the direction of flow)}$$

and

$$F_Y = \frac{waV^2}{2g} \times \sin 2\theta \text{ (in a direction normal to flow)}$$

(*c*) When a jet of water enters and leaves the curved fixed plate or vane tangentially, then the force of the jet along normal to the plate

$$= \frac{waV^2}{g}(\cos\alpha + \cos\beta)$$

where α and β = Inlet and outlet angles of the jet respectively.

(*d*) Force exerted by a jet of water impinging normally on a plate which due to the impact of jet, moves in the direction of jet with a velocity v is

$$= \frac{wa}{g}(V-v)^2$$

(*e*) When a jet of water enters and leaves a moving curved vane, then the force of jet in the direction of motion of the vane is

$$= \frac{waV}{g}(V_w - V_{w1})$$

where V_w and V_{w1} = Velocity of whirl at inlet and outlet respectively.

*This equation may be written as

$$*F_X = \rho a V^2 \text{ (in newton)}$$

where ρ = Mass density of water in kg / m³ = w/g

4.3 Hydraulic Turbines

A hydraulic turbine is a machine which converts the hydraulic energy into mechanical energy. The hydraulic turbines are also known as *water turbines*. Following two types of hydraulic turbines are important.

1. Impulse turbine; and 2. Reaction turbine

In an *impulse turbine*, the total energy at the inlet of a turbine is only kinetic energy. The pressure of water both at entering and leaving the vanes is atmospheric. It is used for high head of water. A Pelton wheel is a tangential flow impulse turbine.

In a *reaction turbine*, the total energy at the inlet of a turbine is kinetic energy as well as pressure energy. It is used for low head of water. The Francis and Kaplan turbines are inward flow and axial flow reaction turbines respectively.

4.4 Impulse Turbines

The following important points may be noted for impulse turbines :

(*a*) The hydraulic efficiency of an impulse turbine is the ratio of the workdone on the wheel to the energy of the jet.

(*b*) The hydraulic efficiency of an impulse turbine is maximum when the velocity of wheel is one-half the velocity of jet of water at inlet.

(*c*) The maximum hydraulic efficiency of an impulse turbine is given by

$$\eta_{max} = \frac{1 + \cos\phi}{2}$$

where ϕ = Angle of blade tip at outlet.

(*d*) The mechanical efficiency of an impulse turbine is the ratio of the actual work available at the turbine to the energy inparted to the wheel.

(*e*) The overall efficiency of an impulse turbine is the ratio of the actual power produced by the turbine to the energy actually supplied by the turbine.

(*f*) The width of the bucket for a Pelton wheel is generally five times the diameter of jet.

(*g*) The depth of the bucket for a Pelton wheel is generally 1.2 times the diameter of jet.

(*h*) The number of buckets on the periphery of a Pelton wheel is given by $\left(\frac{D}{2d} + 15\right)$, where D is the pitch diameter of the wheel and d is the diameter of the jet.

(*i*) The ratio of D / d is called jet ratio.

(*j*) The maximum number of jets, generally, employed on Pelton wheel are six.

4.5 Reaction Turbines

The following important points may be noted for reaction turbines :

(*a*) In a reaction turbine, the water enters the wheel under pressure and flows over the vanes.

(*b*) The hydraulic efficiency of a reaction turbine is the ratio of the workdone on the wheel to the energy (or head of water) actually supplied to the turbine.

(*c*) The overall efficiency of a reaction turbine is the ratio of the power produced by the turbine to the energy actually supplied by the turbine.

(*d*) A Kaplan turbine is an axial flow reaction turbine. The number of blades are generally 4 to 8 in a Kaplan turbine runner.

(*e*) A Francis turbine is an outward flow reaction turbine. The number of blades are generally 16 to 24 in a Francis turbine runner.

4.6 Draft Tube

The draft tube is a pipe of gradually increasing area used for discharging water from the exit of a reaction turbine. It is an integral part of mixed and axial flow turbines. Because of the draft tube, it is possible to have the pressure at runner outlet much below the atmospheric pressure.

The efficiency of a draft tube is defined as the ratio of net gain in pressure head to the velocity head at entrance of draft tube.

4.7 Specific Speed

The specific speed of a turbine is defined as the speed of an imaginary turbine, identical with the given turbine, which develops unit power under unit head. Mathematically, specific speed,

$$N_S = \frac{N\sqrt{P}}{H^{5/4}}$$

where P = Power, and

H = Net head on turbine.

The specific speed plays an important role in the selection of a type of turbine. By knowing the specific speed of a turbine, the performance of the turbine can also be predicted.

4.8 Unit Speed, Unit Discharge and Unit Power

The unit speed is the speed of the turbine operating under one metre head. Mathematically,

unit speed, $$N_u = \frac{N}{\sqrt{H}}$$

The unit discharge is the discharge through a turbine when the head on the turbine is unity. Mathematically, unit discharge,

$$Q_u = \frac{Q}{\sqrt{H}}$$

The unit power is the power developed by a turbine when the head on the turbine is unity. Mathematically, unit power,

$$P_u = \frac{P}{H^{3/2}}$$

4.9 Cavitation

The formation, growth and collapse of vapour filled cavities or bubbles in a flowing liquid due to local fall in fluid pressure is called *cavitation*. The cavitation in a hydraulic machine affects in the following ways :

(*a*) It causes noise and vibration of various parts.

(*b*) It makes surface rough.

(*c*) It reduces the discharge of a turbine.

(*d*) It causes sudden drop in power output and efficiency.

The cavitation in reaction turbines can be avoided to a great extent by using the following methods:

(*a*) By installing the turbine below the tail race level.

(*b*) By using stainless steel runner of the turbine.

(*c*) By providing highly polished blades to the runner.

(*d*) By running the turbine runner to the designed speed.

4.10 Centrifugal Pumps

A centrifugal pump is a machine which converts the kinetic energy of the water into pressure energy before the water leaves its casing. The flow of water leaving the impeller is free vortex. The impeller of a centrifugal pump may have volute casing, vortex casing and volute casing with guide blades.

The following important points may be noted for centrifugal pumps :

(*a*) The manometric head is the actual head of water against which a centrifugal pump has to work. It may be obtained by using the following relations, *i.e.*,

Manometric head = Workdone per kg of water – Losses within the impeller

= Energy per kg at outlet of impeller – Energy per kg at inlet of impeller

= Suction lift + Loss of head in suction pipe due to friction + Delivery lift + Loss of head in delivery pipe due to friction + Velocity head in the delivery pipe.

(*b*) The discharge (Q) of a centrifugal pump is given by

$$Q = \pi D.\, b.\, V_f$$

where

D = Diameter of impeller at inlet,

b = Width of impeller at inlet, and

V_f = Velocity of flow at inlet.

(*c*) The manometric efficiency of a centrifugal pump is defined as the ratio of the manometric head to the energy supplied by the impeller.

(*d*) The mechanical efficiency of a centrifugal pump is defined as the ratio of energy available at the impeller to the energy supplied to the pump by the prime mover.

(*e*) The overall efficiency of a centrifugal pump is defined as the energy supplied to the pump to the energy available at the impeller.

(*f*) The efficiency of a centrifugal pump will the maximum when the blades are bent backward.

(*g*) The power required to drive a centrifugal pump is given by

$$P = \frac{w.Q.H_m}{\eta_o} \text{ (in kW)}$$

where

w = Specific weight of water in kN/m^3,

Q = Discharge of the pump in m^3/s,

H_m = Manometric head in metres, and

η_o = Overall efficiency of the pump.

4.11 Multistage Centrifugal Pumps

The multistage centrifugal pumps are those which have two or more identical impellers mounted on the same shaft or on different shafts. They are used to produce high heads or to discharge a large quantity of liquid. In order to obtain a high head, a number of impellers are mounted in series or on the same shaft while to discharge a large quantity of liquid, the impellers are connected in parallel.

4.12 Specific Speed of Centrifugal Pump

The specific speed of a centrifugal pump is defined as the speed of an imaginary pump, identical with the given pump, which will discharge 1 litre of water, while it is being raised through a head of one metre. Mathematically, specific speed,

$$N_S = \frac{N\sqrt{Q}}{H_m^{3/4}}$$

The ranges of specific speeds for different types of pumps are given in the following table.

Type of pump	Slow speed with radial flow at outlet	Medium speed with radial flow at outlet	High speed with radial flow at outlet	High speed with mixed flow at outlet	High speed with axial flow at outlet
Specific speed in r.p.m.	10 – 30	30 – 50	50 – 80	80 – 160	160 – 500

4.13 Net Positive Suction Head (NPSH)

The net positive suction head (NPSH) is defined as the difference between the net inlet head and the head corresponding to the vapour pressure of the liquid. It may be noted that when the pressure at the suction falls below the vapour pressure of the liquid, then cavitation will be formed.

4.14 Model Testing and Similarity of Pumps

In order to know the performance of the prototypes, the models of centrifugal pumps are tested.

When the ratio of all the corresponding linear dimensions of the model and the prototype are equal, then they are said to have *geometric similarity*. In other words, geometric similarity is said to exist between the model and the prototype, if both of them are identical in shape, but differ only in size.

When the ratio of corresponding velocities at corresponding points are equal, then the model and the prototype are said to have *kinematic similarity*.

When the ratio of corresponding forces acting at corresponding points are equal, then the model and the prototype are said to have *dynamic similarity*.

4.15 Reciprocating Pump

The reciprocating pump is a positive displacement pump as it discharges a definite quantity of liquid during the displacement of its piston or plunger which executes a reciprocating motion in a closely fitting cylinder. It is best suited for less discharge and higher heads.

The following important points may be noted for the reciprocating pump:

(*a*) Discharge through a reciprocating pump,

$$Q = LAN/60 \text{ (in m}^3\text{/s)} \qquad \text{...(For single acting)}$$

$$= 2\,LAN/60 \qquad \text{...(For double acting)}$$

where

L = Length of the stroke in metres,

A = Cross-sectional area of the piston in m^2, and

N = Speed of the crank in r.p.m.

(*b*) Power required to drive a reciprocating pump

$$= w\,Q\,(H_s + H_d) \text{ (in watts)} \qquad \text{...(For single acting)}$$

$$= 2\,w\,Q\,(H_s + H_d) \text{ (in watts)} \qquad \text{...(For double acting)}$$

where

w = Weight density or specific weight of the liquid in N/m^3,

H_s = Suction head of the pump in metres, and

H_d = Delivery head of the pump in metres.

(*c*) The difference between the theoretical discharge and the actual discharge is called the *slip* of the pump.

(*d*) The slip of a reciprocating pump is negative when the suction pipe is long and delivery pipe is short and the pump is running at high speeds.

4.16 Air Vessels

The air vessel, in a reciprocating pump, is a cast iron closed chamber having an opening at its base. These are fitted to the suction pipe and delivery pipe close to the cylinder of the pump. The vessels are used for the following purposes:

(a) To get continuous supply of liquid at a uniform rate.

(b) To save the power required to drive the pump. This is due to the fact that by using air vessels, the acceleration and friction heads are reduced. Thus the work is also reduced.

It may be noted that by fitting an air vessel to the reciprocating pump, the saving of work and subsequently the power is about 84.8 % in case of a single acting reciprocating pump and 39.2 % in case of double acting reciprocating pump.

4.17 Miscellaneous Hydraulic Machines

The following are the miscellaneous hydraulic machines:

(a) *Hydraulic press.* It is a device used to lift larger load by the application of a comparatively much smaller force. It is based on Pascal's law.

The efficiency of a hydraulic press is given by

$$\eta = \frac{W}{P} \times \frac{a}{A}$$

where W = Weight lifted by ram,

P = Force applied on plunger,

A = Area of ram, and

a = Area of plunger.

(b) *Hydraulic ram.* It is a device used to lift small quantity of water to a greater height when a large quantity of water is available at a smaller height. It works on the principle of water hammer.

(c) *Hydraulic accumulator.* It is a device used to store pressure energy which may be supplied to hydraulic machines such as presses, lifts and cranes.

(d) *Hydraulic intensifier.* It is device used to increase the intensity of pressure of water by means of energy available from a large quantity of water at a low pressure.

(e) *Hydraulic crane.* It is a device used to lift heavy loads. It is widely used in docks for loading and unloading ships, ware houses, foundry workshops and heavy industries.

(f) *Hydraulic lift.* It is a device used for carrying persons and loads from one floor to another, in a multistoreyed building.

OBJECTIVE TYPE QUESTIONS

1. The force exerted (in newton) by a jet of water impinging normally on a fixed plate is

(a) $\frac{waV}{2g}$ (b) $\frac{waV}{g}$ (c) $\frac{waV^2}{2g}$ (d) $\frac{waV^2}{g}$

where w = Specific weight of water in N/m^3,

a = Cross-sectional area of jet in m^2, and

V = Velocity of jet in m/s.

2. The force exerted by a jet of water (in a direction normal to flow) impinging on a fixed plate inclined at an angle θ with the jet is

(a) $\frac{waV}{2g} \times \sin\theta$ (b) $\frac{waV}{g} \times \sin\theta$ (c) $\frac{waV^2}{2g} \times \sin 2\theta$ (d) $\frac{waV^2}{2g} \times \sin 2\theta$

3. The force exerted by a jet of water impinging normally on a plate which due to the impact of jet, moves in the direction of jet with a velocity v is

(a) $\frac{wa(V-v)}{2g}$ (b) $\frac{wa(V-v)}{g}$ (c) $\frac{wa(V-v)^2}{2g}$ (d) $\frac{wa(V-v)^2}{g}$

4. A jet of water enters and leaves a fixed curved vane tangentially. The force of jet along perpendicular to the vane is zero.

(a) True (b) False

5. A jet of water enters and leaves a fixed curved vane tangentially. The force of the jet along normal to the vane is

(a) $\frac{waV^2}{g}(\cos\alpha + \cos\beta)$ (b) $\frac{waV^2}{g}(\cos\alpha - \cos\beta)$

(c) $\frac{waV^2}{g}(\sin\alpha + \sin\beta)$ (d) $\frac{waV^2}{g}(\sin\alpha - \sin\beta)$

where α and β = Inlet and outlet angles of the jet respectively.

6. A jet of water enters and leaves a moving curved vane. The force of jet in the direction of motion of the vane is

(a) $\frac{waV}{g}(V_w + V_{w1})$ (b) $\frac{waV}{g}(V_w - V_{w1})$

(c) $\frac{waV^2}{g}(V_w + V_{w1})$ (d) $\frac{waV^2}{g}(V_w - V_{w1})$

where V_w and V_{w1} = Velocities of whirl at inlet and outlet respectively.

7. The ratio of the normal force of jet of water on a plate inclined at an angle θ as compared to that when the plate is normal to jet, is

(a) $1/\sqrt{2}$ (b) $1/2$ (c) 1 (d) $\sqrt{2}$

8. A jet of water is striking at the centre of a curved vane moving with a uniform velocity in the direction of jet. For the maximum efficiency, the vane velocity is .... of the jet velocity

(a) one-half (b) one-third (c) two-third (d) three-fourth

9. The principle of jet propulsion is used in driving the ships and aeroplanes.

(a) Correct (b) Incorrect

10. A ship with jet propulsion draws water through inlet orifices at right angles to the direction of its motion. The propelling force of the jet is

(a) $\frac{waV_r}{g}(V_r + v)$ (b) $\frac{waV_r}{g}(V_r - v)$ (c) $\frac{waV_r}{g}(V_r + v)^2$ (d) $\frac{waV_r}{g}(V_r - v)^2$

where a = Area of the jet,

V_r = Relative velocity of the jet and ship = $V + v$,

v = Velocity of the ship, and

V = Velocity of the jet issuing from the ship.

ANSWERS

1. (d)	2. (c)	3. (d)	4. (b)	5. (a)	6. (b)
7. (b)	8. (b)	9. (a)	10. (b)	11. (a)	12. (a)
13. (b)	14. (b)	15. (b)	16. (a)	17. (a)	18. (d)
19. (b)	20. (a)	21. (a)	22. (b)	23. (b)	24. (a)
25. (a)	26. (b)	27. (d)	28. (c)	29. (b)	30. (a)
31. (b)	32. (a)	33. (c)	34. (d)	35. (b)	36. (d)
37. (b)	38. (c)	39. (d)	40. (c)	41. (c)	42. (a)
43. (b)	44. (d)	45. (c)	46. (b)	47. (c)	48. (c)
49. (a)	50. (b)	51. (a)	52. (c)	53. (b)	54. (b)
55. (a)	56. (a)	57. (d)	58. (b)	59. (d)	60. (c)
61. (b)	62. (b)	63. (a)	64. (a)	65. (b)	66. (a)
67. (c)	68. (a)	69. (d)	70. (c)	71. (c)	72. (a)
73. (a)	74. (a)	75. (a)	76. (c)	77. (b)	78. (c)
79. (b)	80. (a)	81. (c)	82. (c)	83. (b)	84. (a)
85. (b)*	86. (b)	87. (a)	88. (a)	89. (b)	90. (c)
91. (b)	92. (c)	93. (a)	94. (c)	95. (d)	96. (d)
97. (d)	98. (d)	99. (c)	100. (B), (D), (C), (A)		101. (b)
102. (a)	103. (d)	104. (a)	105. (d)	106. (b)	107. (a)
108. (c)	109. (a)	110. (b)	111. (d)	112. (c)	113. (b)
114. (a)	115. (b)	116. (d)	117. (c)	118. (a)	119. (a)
120. (d)	121. (c)	122. (d)	123. (c)	124. (d)	125. (a)
126. (a)	127. (a)	128. (d)	129. (c)	130. (a)	131. (a)
132. (a)	133. (c)	134. (d)	135. (b)	136. (d)	137. (a)
138. (b)	139. (c)	140. (a)	141. (c)	142. (d)	143. (b)
144. (b)	145. (d)	146. (b)	147. (d)	148. (a)	149. (a)
150. (a)	151. (d)	152. (a)	153. (b)	154. (c)	155. (c)
156. (d)	157. (a)	158. (d)	159. (d)	160. (c)	161. (d)
162. (c)	163. (c)	164. (c)	165. (d)	166. (b)	167. (a)
168. (a)	169. (c)	170. (c)			

5

Thermodynamics

5.1 Introduction

The Thermodynamics is that branch of Engineering – science which deals with the energies possesed by gases and vapours. It also includes the conversion of these energies in terms of heat and mechanical work and their relationship with properties of the system.

5.2 Thermodynamic System

The thermodynamic system may be defined as a definite area or a space where some *thermodynamic process takes place. It may be noted that a thermodynamic system has its boundaries, and anything outside the boundaries is called its surroundings. The thermodynamic system may be classified into the following three groups :

1. *Closed system.* This is a system of fixed mass whose boundaries are determined by the space of the working substance occupied in it. In a closed system, heat and work cross the boundary of the system, but there is no addition or loss of the originial mass of the working substance. Thus the mass of the working substance which comprises the system, is fixed.

2. *Open system.* In this system, the working substance crosses the boundary of the system. The heat and work may also cross the boundary.

3. *Isolated system.* It is a system of fixed mass and no heat or work cross its boundary.

5.3 Properties of a System

The state of a system may be identified by certain observable quantities such as volume, temperature, pressure and density etc. All the quantities which identify the state of a system are called properties. The thermodynamic properties are divided into the following two classes :

1. *Extensive properties.* The properties of the system, whose value for the entire system is equal to the sum of their values for the individual parts of the system, are called extensive properties. For example, total volume, total mass and total energy of a sysem are extensive properties.

2. *Intensive properties.* The properties of the system, whose value for the entire system is not equal to the sum of their values for the individual parts of the system, are called extensive properties. For example, temperature, pressure and density of a system are intensive properties.

5.4 Thermal Equilibrum

When there are variations in temperature from point to point of an isolated system, the temperature at every point first changes with time. This rate of change decreases and eventually stops. When no further changes are observed, the system is said to be in thermal equilibrium.

5.5 Laws of Thermodynamics

Following are the three laws of thermodynamics :

1. *Zeroth law of thermodynamics.* This law states that *when two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other.*

*See Art. 5.14.

First law of thermodynamics. This law states that the *heat and mechanical work are mutually convertible.* According to this law, a definite amount of mechanical work is needed to produce a definite amount of heat and vice versa.

This law also states that *the energy can neither be created nor destroyed, through it can be transformed from one form to another.* According to this law, the energy due to heat supplied (Q) must be balanced by the external workdone (W) plus the gain in internal energy (E) due to rise in temperature. In other words,

$$Q = W + E$$

3. *Second law of thermodynamics.* This law states that *there is a definite limit to the amount of mechanical energy, which can be obtained from a given quantity of heat energy.*

According to Claussius, this law may be stated as "*It is impossible for a self - acting machine working in a cyclic process, to transfer heat from a body at a lower temperature to a body at a higher temperature without the aid of an external agency*".

The second law of thermodynamics has also been stated by Kelvin-Planck as "*It is impossible to construct an engine working on a cyclic process, whose sole purpose is to convert heat energy in to work.*" According to this statement, the second law of thermodynamics is sometimes called as *law of degradation of energy.*

5.6 Laws of Perfect Gases

A perfect gas (or an ideal gas) may be defined as a state of a substance, whose evaporation from its liquid state is complete. It may be noted that if its evaporation is partial, the substance is called *vapour*. A vapour contains some particles of liquid in suspension. The behaviour of superheated vapours is similar to that of a perfect gas.

The physical properties of a gas are controlled by the following three variables :

1. Pressure exerted by the gas, 2. Volume occupied by the gas, and 3. Temperature of the gas.

The behaviour of a perfect gas, undergoing any change in these three variables, is governed by the following laws :

1. *Boyle's law. This law was formulated by Robert Boyle in 1662. It states, "The absolute pressure of a given mass of a perfect gas varies inversely as its volume, when the temperature remains constant."* Mathematically,

$$p \propto \frac{1}{v} \quad \text{or} \quad pv = \text{Constant}$$

The more useful form of the above equation is :

$$p_1 v_1 = p_2 v_2 = p_3 v_3 = \ldots = \text{Constant}$$

where suffixes $_{1, 2}$ and $_3$ ..... refer to different sets of conditions.

2. *Charles' law.* This law was formulated by a Frenchman Jacques A.C. Charles in about 1787. It may be stated in two different forms :

(*i*) "*The volume of a given mass of a perfect gas varies directly as its absolute temperature, when the absolute pressure remains constant.*" Mathematically,

$$v \propto T \quad \text{or} \quad \frac{v}{T} = \text{Constant}$$

or
$$\frac{v_1}{T_1} = \frac{v_2}{T_2} = \frac{v_3}{T_3} = \ldots\ldots = \text{Constant}$$

where suffixes $_{1, 2}$ and $_3$ .....refer to different sets of conditions.

(*ii*) "*All perfect gases change in volume by 1 / 273 th of its original volume at 0° C for every 1°C change in temperature, when the pressure remains constant.*"

Let v_0 = Volume of a given mass of gas at 0° C, and

v_t = Volume of the same mass of gas at t° C.

Then, according to the above statement,

$$v_t = v_0 + \frac{1}{273} v_0 t = v_0 \left(\frac{273+t}{273}\right) = v_0 \times \frac{T}{T_0}$$

or
$$\frac{v_t}{T} = \frac{v_0}{T_0}$$

where T = Absolute temperature corresponding to t° C.

T_0 = Absolute temperature corresponding to 0° C.

A little consideration will show, that the volume of a gas goes on decreasing by 1/ 273th of its original volume for every 1°C decrease in temperature. It is thus obvious, that at a temperature of − 273° C, the volume of the gas would become zero. The temperature at which the volume of a gas becomes zero is called *absolute zero temperature.*

3. *Gay – Lussac law.* This law states, "*The absolute pressure of a given mass of a perfect gas varies directly as its absolute temperature, when the volume remains constant.*" Mathematically

$$p \propto T \quad \text{or} \quad \frac{p}{T} = \text{Constant}$$

or
$$\frac{p_1}{T_1} = \frac{p_2}{T_2} = \frac{p_3}{T_3} = \ldots\ldots = \text{Constant}$$

where suffixes $_{1, 2}$ and $_3$ ..... refer to different sets of conditions.

Note : In dealing with a perfect gas, the values of pressure and temperature are expressed in absolute units.

5.7 General Gas Equation

The gas laws as discussed in Art. 5.6 give us the relation between the two variables when the third variable is constant. But in actual practice, all the three variables *i.e.*, pressure, volume and temperature, change simulataneously. In order to deal with all practical cases, the Boyle's law and Charles' law are combined together, which give us a *general gas equation.*

According to Boyle's law

$$p \propto \frac{1}{v} \quad \text{or} \quad v \propto \frac{1}{p} \qquad \text{... (Keeping } T \text{ constant)}$$

and according to Charles' law

$$v \propto T \qquad \text{... (Keeping } p \text{ constant)}$$

It is obvious that

$$v \propto \frac{1}{p} \text{ and } T \text{ both} \quad \text{or} \quad v \propto \frac{T}{p}$$

$$\therefore \quad pv \propto T \quad \text{or} \quad pv = CT$$

where C is a constant, whose value depends upon the mass and properties of the gas concerned.

The more useful form of the general gas equation is :

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2} = \frac{p_3 v_3}{T_3} = \ldots\ldots = \text{Constant}$$

where suffixes $_{1, 2}$ and $_3$ ...... refer to different sets of conditions.

5.8 Characteristic Equation of a Gas

It is a modified form of general gas equation. If the volume (v) in the general gas equation is taken as that of 1 kg of gas (known as its specific volume, and denoted by v_s), then the constant C (in the general gas equation) is represented by another constant R (in the characteristic equation of gas). Thus, the general gas equation may be rewritten as :

$$p.v_s = RT$$

where R is known as characteristic gas constant or simply gas constant.

For any mass m kg of a gas, the characteristic gas equation becomes :

$$m.pv_s = mRT \quad \text{or} \quad pv = m\,RT \qquad ...(\because m.v_s = v)$$

Notes : 1. In S.I. units, the pressure is expressed in bar (1 bar = 100 kN / m^2).

2. The unit of gas constant (R), in S.I. units, is N-m / kg K or J / kg K ($\because$ 1 N-m = 1 J)

3. The value of gas constant (R) is different for different gases. Its value for atmospheric air is taken 287 J / kg K or 0.287 kJ / kg K.

4. The equation $pv = mRT$ may also be expressed in another form *i.e.*,

$$p = \frac{m}{v} RT = \rho RT \qquad ...\left(\because \frac{m}{v} = \rho\right)$$

where ρ (rho) is the density of the given gas.

5.9 Joule's Law

It states, "*The change of internal energy of a perfect gas is directly proportional to the change of temperature.*" Mathematically

$$dE \propto dT = m.C\,dT$$

where

m = Mass of the gas, and

C = A constant of proportionality, known as specific heat.

Note : From the Joule's law, we see that whenever a gas expands, without doing any external work and without taking in or giving out heat, its internal energy as well as temperature does not change.

5.10 Avogadro's Law

It states, "*Equal volumes of all gases, at the same temperature and pressure, contain equal number of molecules.*"

Thus, according to Avogadro's law, 1 m^3 of oxygen (O_2) will contain the same number of molecules as 1 m^3 of hydrogen (H_2) when the temperature and pressure is the same. A little consideration will show, that as the molecular mass of hydrogen is 2 and that of oxygen is 16, therefore a molecule of oxygen has a mass which is 32 / 2 = 16 times the mass of hydrogen molecules. Moreover, as 1m^3 of these two gases contain the same number of molecules, and a molecule of oxygen has a mass 16 times than that of hydrogen molecule, therefore it is evident that density (or specific mass) of oxygen is 16 times the density of hydrogen. Hence, the Avogadro's law indicates that the density (or specific mass) of any two gases is directly proportional to their molecular masses, if the gases are at the same temperatrure and pressure.

Note : The molecular mass expressed in g (*i.e.* 1 g-mole) of all gases, at normal temperature and pressure (briefly written as N.T.P.), occupies a volume of 22.4 litres.

5.11 Universal Gas Constant or Molar Constant

The universal gas constant or molar constant (generally denoted by R_u) of a gas is the product of the gas constant and the molecular mass of the gas. Mathematically,

$$R_u = MR$$

where

M = Molecular mass of the gas expressed in kg-mole, and

R = Gas constant.

In general, if M_1, M_2, M_3, etc. are the molecular masses of different gases and R_1, R_2, R_3, etc. are their gas constants respectively, then

$$M_1R_1 = M_2R_2 = M_3R_3 ... = R_u$$

Notes : 1. The value of R_u is same for all gases.

2. In S.I. units, the value of R_u is taken as 8314 J / kg-mole K or 8.314 kJ / kg-mole K.

3. The characteristic gas equation (*i.e.* $pv = RT$) may be written in terms of molecular mass as :

$$pv = MRT$$

5.12 Specific Heats of a Gas

The specific heat of a substance may be broadly defined as the amount of heat required to raise the temperature of its unit mass through 1°. All the liquids and solids have one specific heat only. But a gas can have any number of specific heats (lying between zero and infinity) depending upon the conditions, under which it is heated.

Following are the two types of specific heats of a gas :

1. *Specific heat at constant volume.* It is the amount of heat required to raise the temperature of a unit mass of gas through 1°, when it is heated at a constant volume. It is generally denoted by c_v.

Let

m = Mass of the gas,

T_1 = Initial temperature of the gas, and

T_2 = Final temperature of the gas.

$\therefore$ Total heat supplied to the gas at constant volume,

$$Q = \text{Mass} \times \text{Sp.heat at constant volume} \times \text{Rise in temperature}$$

$$= m.\,c_v(T_2 - T_1)$$

A little consideration will show, that whenever a gas is heated at constant volume, no work is done by the gas. The whole heat energy is utilised in increasing the temperature and pressure of the gas. In other words, all the amount of heat supplied remains within the body of the gas, and represents the increase in internal energy of the gas.

Note : When the specific heat at constant volume (c_v) is multiplied by the molecular mass of a gas (M), it is called volumetric or molar specific heat at constant volume. It is denoted by c_{vm}. Mathematically

$$c_{vm} = M.c_v$$

2. *Specific heat at constant pressure.* It is the amount of heat required to raise the temperature of a unit mass of a gas through 1°, when it is heated at constant pressure. It is generally denoted by c_p.

Let

m = Mass of the gas,

T_1 = Initial temperature of the gas,

v_1 = Initial volume of the gas, and

T_2, v_2 = Corresponding values for the final conditions of the gas.

$\therefore$ Total heat supplied to the gas as constant pressure,

$$Q = \text{Mass} \times \text{Sp. heat at constant pressure} \times \text{Rise in temperature}$$
$$= m.c_p (T_2 - T_1)$$

Whenever a gas is heated at a constant pressure, the heat supplied to the gas is utilised for the following two purposes :

1. To raise the temperature of the gas. This heat remains within the body of the gas, and represents the increase in internal energy. Mathematically, increase in internal energy,

$$dU = m.c_v (T_2 - T_1)$$

2. To do some external work during expansion. Mathematically, workdone by the gas,

$$W = p(v_2 - v_1) = m.R\,(T_2 - T_1)$$

It is thus obvious, that the specific heat at constant pressure is higher than the specific heat at constant volume.

Note: When the specific heat at constant pressure (c_p) is multiplied by the molecular mass of a gas (M), it is called volumetric or molar specific heat at constant pressure. It is denoted by c_{pm}. Mathematically,

$$c_{pm} = M.c_p$$

5.13 Relation Between Specific Heats

The following relations between the two specific heats (*i.e.* c_p and c_v) are important.

1. The difference of two specific heats is equal to gas constant (R), *i.e.*

$$c_p - c_v = R$$

2. The ratio of two specific heats (*i.e.* c_p / c_v) is known as *adiabatic index* and it is represented by a Greek letter gamma (γ).

We know that $\quad c_p - c_v = R \quad$ or $\quad \dfrac{c_p}{c_v} = 1 + \dfrac{R}{c_v}$

$$\therefore \quad \gamma = 1 + \frac{R}{c_v}$$

Since c_p is always greater than c_v, therefore the value of γ is always greater than unity.

Note : The value of γ for air is 1.4.

5.14 Thermodynamic Processes of Perfect Gases

The process of heating or cooling of a gas is defined as a *thermodynamic process*. It has been observed that during a *thermodynamic process*, change takes place in various properties of the gas such as pressure, volume, temperature, specific energy, specific enthalpy etc. The following thermodynamic processes are important :

1. *Constant volume process or isochoric process.* When the gas is heated at a constant volume, its temperature and pressure will increase. Since there is no change in its volume, no external work is done by the gas. All the heat supplied is stored in the body of the gas in the form of internal energy. It may be noted that this process is governed by Gay-Lussac law.

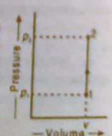


Fig. 5.1

Now consider m kg of a certain gas being heated at a constant volume from an initial temperature T_1 to final temperatuire T_2. This process is shown on the p-v (*i.e.* pressure-volume)* diagram in Fig. 5.1

* It may be noted that the area below the p–v diagram of a thermodynamic process represents the work done during the process to some scale.

We know that

$$Q_{1-2} = (U_2 - U_1) + W_{1-2}$$
$$= U_2 - U_1 \qquad \ldots (\because W_{1-2} = 0)$$

We also know that the internal energy

$$U_2 - U_1 = m.c_v (T_2 - T_1)$$

$\therefore$ Heat supplied, $\quad Q_{1-2} = (U_2 - U_1) = m.c_v (T_2 - T_1)$

Notes : (a) During expansion or heating process, work is done by the gas (*i.e.* W_{1-2} is + ve); internal energy of the gas decreases (*i.e.* dU is – ve) and heat is supplied to the gas (*i.e.* Q_{1-2} is + ve).

(b) During compression or cooling process, work is done on the gas (*i.e.* W_{1-2} is – ve); internal energy of the gas increases (*i.e.* dU is + ve) and heat is rejected by the gas (*i.e.* Q_{1-2} is – ve).

2. *Constant pressure process or isobaric process.* When the gas is heated at a constant pressure, its temperature and volume will increase. Since there is a change in its volume, the heat supplied is utilised in increasing the internal energy of the gas, and also for doing some external work. It may be noted that this process is governed by Charles' law.

Now consider m kg of a certain gas being heated at a constant pressure from an initial temperature T_1 to a final temperature T_2. This process is shown on the p-v diagram in Fig. 5.2.

We know that heat supplied to the gas at constant pressure,

$$Q_{1-2} = m.c_p (T_2 - T_1)$$

Increase in internal energy,

$$U_2 - U_1 = m.c_v (T_2 - T_1)$$

and work done during the process or by the gas,

$$W_{1-2} = \text{Area below the line } 1-2$$
$$= p(v_2 - v_1) = m.R(T_2 - T_1)$$

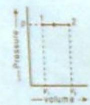


Fig. 5.2

Note : When the gas is cooled at constant pressure, there will be a compression. The temperature and volume will decrease during cooling and work is said to be done on the gas. In this case,

Heat rejected by the gas, $\quad Q_{1-2} = m.c_p (T_1 - T_2)$

Decrease in internal energy, $\quad U_1 - U_2 = m.c_v (T_1 - T_2)$

and workdone on the gas, $\quad W_{1-2} = p\,(v_1 - v_2) = mR\,(T_1 - T_2)$

3. *Hyperbolic process.* A process, in which the gas is heated or expanded in such a way that the product of its pressure and volume (*i.e.* $p \times v$) remains constant, is called a *hyperbolic process.* This process is governed by Boyle's law, *i.e.* $p.v$ = constant. If we plot a graph for pressure and volume, during the process, we get a rectangular hyperbola and hence this process is known as *hyperbolic process.* Its practical application is isothermal process as discussed below :

4. *Constant temperature process or isothermal process.* A process, in which the temperature of the working substance remains constant during its expansion or compression, is called *a constant temperature process* or *isothermal process.* This will happen when the working substance remains in a perfect thermal contact with the surroundings, so that the heat 'sucked in' or 'squeezed out' is compensated exactly for the mechanical work done by, or on the gas respectively. It is thus obvious that in an isothermal process:

1. there is no change in temperature, and
2. there is no change in internal energy.

We know that $Q_{1-2} = dU + W_{1-2} = W_{1-2}$ ...($\because dU = 0$)

Hence during isothermal expansion of a gas,

Heat added = Work done by the gas

Similarly, during isothermal compression of a gas,

Heat subtracted = Work done on the gas

A little consideration will show that the isothermal process is governed by Boyle's law. Thus the isothermal equation of a perfect gas is pv = Constant.

Now consider a certain quantity of a perfect gas being expanded isothermally, which is shown by the curve 1–2 in Fig. 5.3.

Let v_1 = Initial volume of gas,

p_1 = Initial pressure of gas,

v_2 = Final volume of gas, and

p_2 = Final pressure of gas.

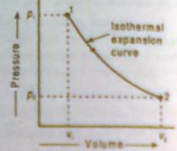


Fig. 5.3

The workdone during isothermal expansion is given by

$$W_{1-2} = \text{Area under the curve 1–2}$$

$$= p_1 v_1 \log_e \left(\frac{v_2}{v_1}\right) = 2.3\, p_1 v_1 \log \left(\frac{v_2}{v_1}\right)$$

$$= 2.3\, mRT \log \left(\frac{v_2}{v_1}\right) = 2.3\, mRT \log \left(\frac{p_1}{p_2}\right) \quad ...(\because p_1 v_1 = p_2 v_2)$$

In general, $W = 2.3\, p_1 v_1 \log r = 2.3\, m R T \log r$

where r is the expansion ratio (when gas is heated) or compression ratio (when gas is cooled).

Notes: (a) $\text{Expansion ratio, } r = \dfrac{\text{Volume at the end of expansion}}{\text{Volume at the beginning of expansion}}$

(b) $\text{Compression ratio, } r = \dfrac{\text{Volume at the beginning of compression}}{\text{Volume at the end of compression}}$

5. *Adiabatic process or isentropic process:* A process, in which the working substance neither receives nor gives out heat to its surroundings, during its expansion or compression is called an **adiabatic process.* This will happen when the working substance remains thermally insulated, so that no heat enters or leaves it during the process. It is thus obvious, that in an adiabatic process:

1. No heat leaves or enters the gas,
2. The temperature of the gas changes, as the work is done at the cost of internal energy, and
3. The change in internal energy is equal to the work done.

We know that $Q_{1-2} = dU + W_{1-2}$ or $dU = -W_{1-2}$ ...($\because Q_{1-2} = 0$)

Minus sign indicates, that for increase in internal energy, work must be done on the gas (*i.e.* –ve work must be done by the gas). Similarly, for decrease in internal energy, work must be done by the gas.

* A frictionless adiabatic process is known as *Isentropic process* (or constant entropy process).

Now consider a certain quantity of a perfect gas being expanded adiabatically which is shown by the curve 1–2 in Fig. 5.4.

Let v_1 = Initial volume of gas,

p_1 = Initial pressure of gas,

v_2 = Final volume of gas, and

p_2 = Final pressure of gas.

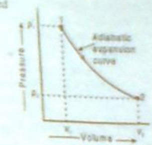


Fig. 5.4

The workdone during adiabatic process is given by

$$W = \frac{p_1 v_1 - p_2 v_2}{\gamma - 1} = \frac{mR\,(T_1 - T_2)}{\gamma - 1} \quad ...(\text{For expansion})$$

$$= \frac{p_2 v_2 - p_1 v_1}{\gamma - 1} = \frac{mR\,(T_2 - T_1)}{\gamma - 1} \quad ...(\text{For compression})$$

Notes : (a) For adiabatic process, $p_1 v_1^\gamma = p_2 v_2^\gamma$ = Constant, where γ is the adiabatic index.

(b) Since $p_1 v_1 = mRT_1$ and $p_2 v_2 = mRT_2$, therefore the above equation may be written as

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma - 1} = \left(\frac{p_1}{p_2}\right)^{\frac{\gamma - 1}{\gamma}}$$

6. *Polytropic process.* The polytropic process is also known as the general law for the expansion and compression of gases and is given by the relation:

$$p.v^n = \text{Constant}$$

where n is a polytropic index, which may have any value from zero to infinity, depending upon the manner, in which the expansion or compression has taken place. The various equations for polytropic process may be expressed by changing the index n for γ in the adiabatic process.

The heat absorbed or rejected during the polytropic process (*i.e.* pv^n = constant) is given by

$$Q = \frac{\gamma - n}{\gamma - 1} \times \text{Workdone} = \frac{\gamma - n}{\gamma - 1} \times \frac{p_1 v_1 - p_2 v_2}{n - 1}$$

$$= \frac{\gamma - n}{\gamma - 1} \times \frac{mR\,(T_1 - T_2)}{n - 1} = \frac{\gamma - n}{\gamma - 1} \times m.c_v\,(T_1 - T_2)$$

Notes : (a) When n is less than γ, then heat is absorbed by the gas.

(b) When n is greater than γ, then heat is rejected by the gas.

(c) The polytropic index (n) is given by

$$n = \frac{\log(p_2/p_1)}{\log(v_1/v_2)}$$

7. *Free expansion (or unresisted expansion) process.* A free expansion occurs when a fluid is allowed to expand suddenly into a vacuum chamber through an orifice of large dimensions. In this process, no heat is supplied or rejected and no external work is done. Hence the total heat of the fluid remains constant. This type of expansion may also be called as constant total heat expansion. It is thus obvious, that in a free expansion process,

$$Q_{1-2} = 0, \quad W_{1-2} = 0 \quad \text{and} \quad dU = 0$$

8. *Throttling process.* When a perfect gas is expanded through an aperture of minute dimensions, such as a narrow throat or a slightly opened valve, the process is termed as *throttling process.* During this process, no heat is supplied or rejected and also no external work is done. Moreover, there is no change in temperature, and so the total heat of the fluid remains constant.

During the throttling process, the expansion of a perfect gas is under constant total heat conditions, and resembles with free expansion process. Thus in a throttling process,

$$Q_{1-2} = 0,\ W_{1-2} = 0 \text{ and } dU = 0.$$

5.15 General Laws for Expansion and Compression

The general law of expansion or compression of a perfect gas is pv^n = Constant. It gives the relationship between pressure and volume of a given quantity of gas. The value of *n* depends upon the nature of gas, and condition under which the changes (*i.e.* expansion or compression) takes place. The value of *n* may be between zero and infinity. But the following values of *n* are important from the subject point of view :

1. When $n = 0$, then pv^0 = Constant, *i.e.* p = Constant. In other words, for the expansion or compression of a perfect gas at *constant pressure*, $n = 0$.
2. When $n = 1$, then pv = Constant, *i.e.* the expansion or compression is *isothermal* or *hyperbolic*.
3. When n lies between 1 and n, the expansion or compression is *polytropic*, *i.e.* pv^n = Constant.
4. When $n = \gamma$, the expansion or compression is *adiabatic*, *i.e.* pv^{γ} = Constant.
5. When $n = \infty$, the expansion or compression is at constant volume, *i.e.* v = Constant.

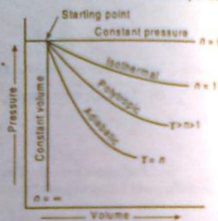


Fig 5.5

Fig 5.5 shows the curves of expansion of a perfect gas for different values of *n*. We see that greater the value of *n*, steeper is the curve of expansion.

5.16 Entropy

It is an important thermodynamic property of a working substance, which increases with the addition of heat, and decreases with its removal. As a matter of fact, it is tedious to define the term entropy. But it is comparatively easy to define change of entropy of a working substance. Over small range of temperature, the increase or decrease of entropy, when multiplied by the absolute temperature, gives the heat absorbed or rejected by the working substance. Mathematically, heat absorbed or rejected by the working substance,

$$\delta Q = T\,dS$$

where T = Absolute temperature, and

δS = Increase or decrease in entropy.

Theoretically, the entropy of a substance is *zero* at *absolute zero temperature.* Hence, in entropy calculations, some convenient datum should be selected from which measurement may be made.

It may be noted that water at 0° C is assumed to have zero entropy, and changes in its entropy are reckoned from this temperature.

5.17 Thermodynamic Cycle

A thermodynamic cycle consists of a series of thermodynamic operations (processes), which take place in a certain order, and the initial conditions are restored at the end of the process. When the operations or processes of cycle are plotted on p-v diagram, they form a closed figure, each operation being represented by its own curve. Since the area under each curve gives the work done to some scale, during each operation, therefore, it follows that the net work done during one cycle will be given by the enclosed area of the diagram as shown shaded in Fig 5.6.

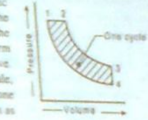


Fig. 5.6

Notes : 1. A cycle, which requires four piston strokes and two complete revolutions of the crank is known as *four-stroke cycle.* But a cycle, which requires only two piston strokes and one revolution of the crank, is known as *two-stroke cycle.*

2. When air is assumed to be the working substance inside the engine cylinder, the cycle is called as an *air cycle.*

5.18 Classification of Thermodynamic Cycles

The thermodynamic cycles are classified into the following groups :

1. *Reversible cycle.* A process, in which some change in the reverse direction, reverses the process completely, is known as a *reversible process.* In a reversible process, there should not be any loss of heat due to friction, radiation or conduction, etc. A cycle will be reversible if all the processes constituting the cycle are reversible. Thus in a reversible cycle, the initial conditions are restored at the end of the cycle.

A little consideration will show, that when the operations are performed in the reversed order, the cycle draws heat from the cold body and rejects it to the hot body. This operation requires an external power to drive the mechanism according to second law of thermodynamics. A machine which operates on a reversed cycle is regarded as a "heat pump", such as a refrigerator, because it pumps heat from the cold body to the hot body. Following are the conditions for reversibility of a cycle:

1. The pressure and temperature of the working substance must not differ, appreciably, from those of the surroundings at any stage in the process.
2. All the processes, taking place in the cycle of operation, must be extremely slow.
3. The working parts of the engine must be friction free.
4. There should be no loss of energy during the cycle of operation.

Note: A reversible cycle should not be confused with a mechanically reversible engine. Steam engine cranks may be made to revolve in a reversed direction by mechanically altering the valve settings. But this does not reverse the cycle, on which it works. A two-stroke petrol engine may be made to revolve in reverse direction by altering the timing of ignition. But this also does not reverse the actual cycle.

2. *Irreversible cycle.* A process, in which change in the reverse direction, does not reverse the process, is called *irreversible process.* In an irreversible process, there is a loss of heat due to friction, radiation or conduction.

In an actual practice, most of the processes are irreversible to some degree. The main causes for the irreversibility are (*i*) mechanical and fluid friction, (*ii*) unrestricted expansion (*iii*) heat transfer with a finite temperature difference. Moreover, friction converts the mechanical work into heat. This heat cannot supply back the same amount of mechanical work, which was consumed for its production. Thus, if there is some friction involved in the process, it becomes irreversible. A cycle will be irreversible if any of the processes, constituting the cycle, is irreversible. Thus in an irreversible cycle, the initial conditions are not restored at the end of the cycle.

Notes : 1. We have discussed the various thermodynamic processes in Art. 5.14. The processes such as constant volume, constant pressure, isothermal or constant temperature (*i.e.* $p.v = C$), adiabatic (*i.e.* $p.v^{\gamma} = C$) and polytropic (*i.e.* $p.v^{n} = C$) are all reversible processes.

2. The throttling is an irreversible process.

5.19 Efficiency of a Cycle

It may be defined as the ratio of work done to the heat supplied during a cycle. Mathematically, efficiency of a cycle,

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}}$$

Since the work done during a cycle is equal to heat supplied *minus* the heat rejected, the efficiency of a cycle, therefore, may also be expressed as

$$\eta = \frac{\text{Heat supplied} - \text{Heat rejected}}{\text{Heat supplied}}$$

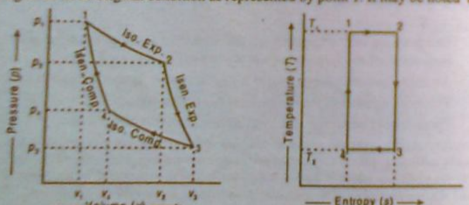
Notes : 1. The efficiency, as given above, is the theoretical efficiency of the cycle. Therefore it is known as *theoretical thermal efficiency*.

2. It does not take into account the practical losses, which occur in running of the engine.

3. In order to compare the efficiency of the thermodynamic cycles, air is assumed to be the working substance inside the engine cylinder. Moreover, air is assumed to behave as a perfect gas. The efficiency, thus, obtained is known as *air standard efficiency*. It is also called *ideal efficiency*.

5.20 Carnot Cycle

This cycle was devised by Nicolas Leonard Sadi Carnot, to analyse the problem of the efficiency of a heat engine. In a Carnot cycle, the working substance is subjected to a cyclic operation consisting of two isothermal and two reversible adiabatic or (isentropic) operations. The p–v and T–s diagram of this cycle is shown in Fig. 5.7 (*a*) and (*b*) respectively. Let the engine cylinder contain m kg of air at its original condition as represented by point 1. It may be noted that



(*a*) p-v diagram. (*b*) T-s diagram.

Fig. 5.7

1. During isothermal expansion, as shown by 1–2 in Fig. 5.7 the heat supplied is fully absorbed by the air and is utilised in doing external work.

$\therefore$ Heat supplied = Workdone by the air during isothermal expansion

$$= p_1 v_1 \log_e \left(\frac{v_2}{v_1}\right) = m R T_1 \log_e r$$

where $$r = \frac{v_2}{v_1} = \text{Expansion ratio.}$$

2. During reversible adiabatic or isentropic expansion, as shown by 2-3 in Fig. 5.7, no heat is absorbed or rejected by the air.

$\therefore$ Decrease in internal energy

= Workdone by the air during adiabatic expansion

$$= \frac{p_2 v_2 - p_3 v_3}{\gamma - 1} = \frac{m R (T_1 - T_2)}{\gamma - 1}$$

3. During isothermal compression, as shown by 3 – 4 in Fig. 5.7, the heat is rejected and is equal to the workdone on the air.

$\therefore$ Heat rejected = Workdone on the air during isothermal compression

$$= p_3 v_3 \log_e \left(\frac{v_3}{v_4}\right) = m R T_2 \log_e r$$

where $$r = \frac{v_3}{v_4} = \text{Compression ratio.}$$

Note: The expansion and compression ratio (r) must be equal, otherwise the cycle would not close.

4. During reversible adiabatic or isentropic compression, as shown by 4 – 1 in Fig 5.7, no heat is absorbed or rejected by the air.

$\therefore$ Increase in internal energy

= Workdone on the air during adiabatic compression

$$= \frac{p_1 v_1 - p_4 v_4}{\gamma - 1} = \frac{m R T_1 - m R T_2}{\gamma - 1}$$

$$= \frac{m R (T_1 - T_2)}{\gamma - 1}$$

We see from the above discussion that the decrease in internal energy during reversible adiabatic expansion 2-3 is equal to the increase in internal energy during reversible adiabatic compression 4 -1. Hence their net effect during the whole cycle is zero. We know that

Work done = Heat supplied — Heat rejected

$$= m R T_1 \log_e r - m R T_2 \log_e r$$

$$= m R \log_e r (T_1 - T_2)$$

and efficiency
$$\eta = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{m R \log_e r (T_1 - T_2)}{m R T_1 \log_e r}$$

$$= \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1}$$

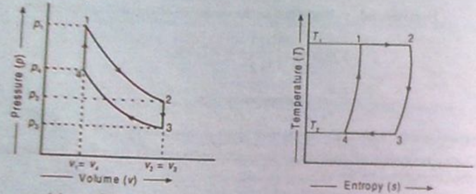
Notes : 1. From the above equation, we see that the efficiency of Carnot's cycle increases as T_1 is increased or T_2 is decreased. In other words, the heat should be taken in at as high a temperature as possible, and rejected at as low a temperature as possible. It may be noted that 100% efficiency can be achieved, only, if T_2 reaches absolute zero, though it is impossible to achieve in practice.

2. It may be noted that it is impossible to make an engine working on Carnot's cycle. The simple reason for the same is that the isothermal expansion 1 - 2 will have to be carried out extremely slow to ensure that the air is always at temperature T_1. Similarly, the isothermal compression 3 - 4 will have to be carried out extremely slow. But reversible adiabatic expansion 2-3 and reversible adiabatic compression 4 - 1 should be carried out as

quickly as possible, in order to approach ideal adiabatic conditions. We know that sudden changes in the speed of an engine are not possible in actual practice. Moreover, it is impossible to completely eliminate friction between the various moving parts of the engine, and also heat losses due to conduction, radiation, etc. It is thus obvious, that it is impossible to realise Carnot's engine in actual practice. However, such an imaginary engine is used as the ultimate standard of comparison of all heat engines.

5.21 Stirling Cycle

This cycle was devised by Robert Stirling in 1845 which consists of two isothermal proceses and two constant volume processes. The last two processes are performed with the help of a regenerator to make this cycle reversible. The p-v and T-s diagrams of this cycle are shown in Fig. 5.8 (a) and (b) respectively.



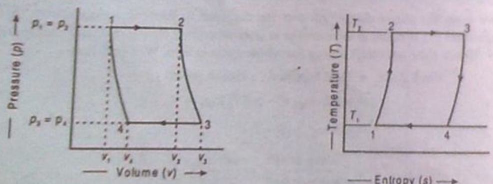
(a) p-v diagram. (b) T-s diagram.

Fig. 5.8

The efficiency of the stirling cycle is same as that of Carnot cycle. This due to the fact that this cycle is reversible and all reversible cycles have the same efficiency.

$\therefore$ Efficiency of Stirling cycle, $\eta = 1 - \dfrac{T_2}{T_1}$

5.22 Ericsson Cycle



(a) p-v diagram. (b) T-s diagram.

Fig. 5.9

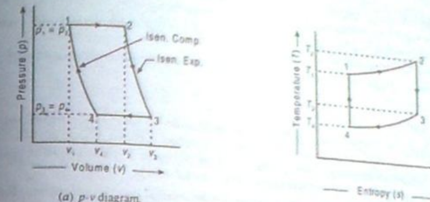
This cycle was devised by J. Ericsson in 1840. It consists of two isothermal and two constant pressure processes.

This cycle is made reversible by the action of a regenerator. The p-v and T-s diagrams of this cycle are shown in Fig 5.9 (a) and (b) respectively. This cycle is mostly used in closed - cycle gas turbines.

The efficiency of the Ericsson cycle is same as that of Carnot cycle, *i.e.*

$$\eta = 1 - \frac{T_1}{T_2} = 1 - \frac{\text{Lowest temperature}}{\text{Highest temperature}}$$

5.23 Joule Cycle



(a) p-v diagram. (b) T-s diagram.

Fig. 5.10

This cycle consists of two constant pressure and two reversible adiabatic or isentropic proceses as shown on p - v and T-s diagram in Fig. 5.10 (a) and (b) respectively. The efficiency of Joule cycle is given by,

$$\eta = 1 - \frac{T_3 - T_4}{T_2 - T_1} = 1 - \frac{T_3\left(1 - \dfrac{T_4}{T_3}\right)}{T_2\left(1 - \dfrac{T_1}{T_2}\right)} \qquad ...(i)$$

We know that reversible adiabatic or isentropic expansion 2 – 3,

$$\frac{T_3}{T_2} = \left(\frac{v_2}{v_3}\right)^{\gamma-1} = \left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} \qquad ...(ii)$$

and for reversible adiabatic or isentropic compression 4 – 1,

$$\frac{T_4}{T_1} = \left(\frac{v_1}{v_4}\right)^{\gamma-1} = \left(\frac{p_4}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \qquad ...(iii)$$

From equations (ii) and (iii),

$$\frac{T_3}{T_2} = \frac{T_4}{T_1} \quad \text{or} \quad \frac{T_1}{T_2} = \frac{T_4}{T_3} \qquad ...(\because p_1 = p_2 \text{ and } p_3 = p_4)$$

and

$$\left(\frac{v_2}{v_3}\right)^{\gamma-1} = \left(\frac{v_1}{v_4}\right)^{\gamma-1} \quad \text{or} \quad \frac{v_2}{v_3} = \frac{v_1}{v_4} = \frac{1}{r} \qquad ...\left(\because r = \frac{v_3}{v_2} = \frac{v_4}{v_1}\right)$$

$$\therefore \frac{T_3}{T_2} = \frac{T_4}{T_1} = \left(\frac{1}{r}\right)^{\gamma-1} = \frac{1}{r^{\gamma-1}}$$

Now equation (i) may be written as

$$\eta = 1 - \frac{1}{r^{\gamma-1}}$$

Notes : 1. The efficiency of the Joule's cycle is lower than Carnot efficiency. The reason is that all the heat is not taken in at the highest temperature and rejected at the lowest temperature.

2. The cycle is not thermodynamically reversible, because there is no regenerator to provide a constant temperature during heating and cooling at constant pressure.

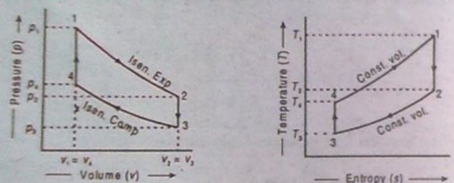
3. The reversed Joule cycle is known as Bell-coleman cycle, and is applied to refrigerators, where air is used as a refrigerant.

5.24 Otto Cycle

This cycle was originally devised by a Frenchman Beau-de-Rochas in 1862. The first successful engine, working on this cycle, was built by a German engineer Nicholas A. Otto in 1876. These days, many gas, petrol and many of the oil engines run on this cycle. It is also known as *constant volume cycle*, as the heat is received and rejected at a constant volume.

This cycle is taken as a standard of comparison for internal combustion engines. For the purpose of comparison with other cycles, the air is assumed to be the working substance.

The ideal Otto cycle consists of two constant volume and two reversible adiabatic or isentropic processes as shown on *p-v* and *T-s* diagrams in Fig. 5.11 (*a*) and (*b*) respectively.



(*a*) *p-v* diagram. (*b*) *T-s* diagram.

Fig. 5.11

The efficiency of the Otto cycle (also known as ideal efficiency or air standard efficiency) is given by

$$\eta = 1 - \frac{T_2 - T_3}{T_1 - T_4} = 1 - \frac{T_3\left(\frac{T_2}{T_3} - 1\right)}{T_4\left(\frac{T_1}{T_4} - 1\right)} \quad \ldots(i)$$

We know that for reversible adiabatic or isentropic expansion process 1-2,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1} = \left(\frac{1}{r}\right)^{\gamma-1} \qquad \left(\because \frac{v_2}{v_1} = r\right) \quad \ldots(ii)$$

and for reversible adiabatic or isentropic compression process 3 - 4,

$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3}\right)^{\gamma-1} = \left(\frac{1}{r}\right)^{\gamma-1} \qquad \ldots\left(\because \frac{v_3}{v_4} = \frac{v_2}{v_1} = r\right) \quad \ldots(iii)$$

From equations (*ii*) and (*iii*),

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} = \left(\frac{1}{r}\right)^{\gamma-1} = \frac{1}{r^{\gamma-1}} \qquad \text{and} \qquad \frac{T_3}{T_3} = \frac{T_1}{T_4}$$

Now equation (*i*) may be written as

$$\eta = 1 - \frac{T_3}{T_4} = 1 - \frac{T_2}{T_1} = 1 - \frac{1}{r^{\gamma-1}} \quad \ldots(iv)$$

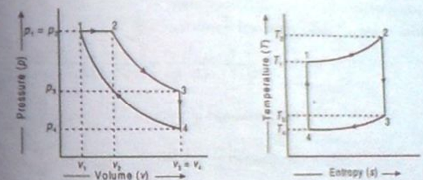
Notes : 1. We see from equation (*iv*) that the efficiency of the Otto cycle depends on compression ratio (*r*).

2. The efficiency increases with the compression ratio (*r*). In actual practice, *r* can not be increased beyond a value of 7 or so.

3. Compression ratio, $r = \dfrac{\text{Total cylinder volume}}{\text{Clearance volume}} = \dfrac{\text{Clearance volume + Stroke volume}}{\text{Clearance volume}}$

$\therefore$ Clearance volume $= \dfrac{\text{Stroke volume}}{r - 1}$

5.25 Diesel Cycle



(*a*) *p-v* diagram. (*b*) *T-s* diagram

Fig. 5.12

This cycle was devised by Dr. Rudolph Diesel in 1893, with an idea to attain a higher thermal efficiency, with a high compression ratio. This is an important cycle on which all the diesel engines work. It is also known as *constant pressure cycle* as heat is received at a constant pressure.

The ideal diesel cycle consists of two reversible adiabatic or isentropic, a constant pressure and a constant volume processes. These processes are represented on a *p-v* and *T-s* diagrams as shown in Fig. 5.12 (*a*) and (*b*) respectively.

The air standard efficiency of this cycle is given by

$$\eta = 1 - \frac{1}{\gamma}\left[\frac{T_3 - T_4}{T_2 - T_1}\right] = 1 - \frac{1}{r^{\gamma-1}}\left[\frac{\rho^{\gamma} - 1}{\gamma(\rho - 1)}\right]$$

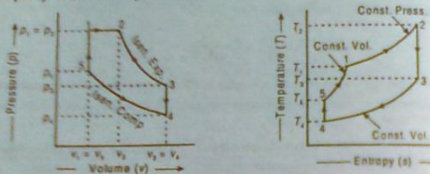
where r = Compression ratio $= \dfrac{v_4}{v_1}$; and ρ = Cut-off ratio $= \dfrac{v_2}{v_1}$

Notes : 1. The efficiency of the ideal diesel cycle is lower than that of Otto cycle, for the same compression ratio.

2. The diesel cycle efficiency increases with decrease in cut-off and approaches maximum (equal to Otto cycle efficiency) when cutoff is zero, *i.e.* $\rho = 1$.

5.26 Dual Combustion Cycle

This cycle is a combination of Otto and Diesel cycles. It is sometimes called semi-diesel cycle, because semi-diesel engines work on this cycle. In this cycle, heat is absorbed partly at a constant volume and partly at a constant pressure.



(a) p-v diagram. (b) T-s diagram.

Fig. 5.13

The ideal dual combustion cycle consists of two reversible adiabatic or isentropic, two constant volume and a constant pressure processes. These processes are represented on p-v and T-s diagrams as shown in Fig 5.13 (*a*) and (*b*) respectively.

The air standard efficiency of this cycle is given by,

$$\eta = 1 - \frac{T_3 - T_4}{\gamma(T_2 - T_1) + (T_1 - T_5)} = 1 - \frac{1}{r^{\gamma - 1}}\left[\frac{\alpha\rho^{\gamma} - 1}{(\alpha - 1) + \gamma . \alpha(\rho - 1)}\right]$$

where

$$r = \text{Compression ratio} = \frac{v_4}{v_5} = \frac{v_3}{v_1}$$

$$\rho = \text{Cut-off ratio} = \frac{v_2}{v_1} = \frac{v_2}{v_5}, \text{ and}$$

$$\alpha = \text{Pressure or expansion ratio} = \frac{p_1}{p_5}$$

Notes : 1. For Otto cycle, $\rho = 1$; and for Diesel cycle, $\alpha = 1$.

2. The efficiency of dual combustion cycle is greater than Diesel cycle and less than Otto Cycle, for the same compression ratio.

5.27 Gas Turbines

A gas turbine is a rotary engine. In a gas turbine plant, the air is compressed in a rotary compressor and passed into a combustion chamber where fuel is burnt. The products of combustion are then made to impinge over rings of turbine blades with high velocity and work is produced.

The gas turbines are classified as follows:

1. *According to the path of working substance*

   (*a*) Closed cycle gas turbines, (*b*) Open cycle gas turbines, and

   (*c*) Semi-closed gas turbines.

2. *According to the process of heat absorption*

   (*a*) Constant pressure gas turbines, and (*b*) Constant volume gas turbines.

5.28 Closed Cycle Gas Turbine

A closed cycle gas turbine, in its simplest form, as shown in Fig 5.14, consists of a compressor, heating chamber, gas turbine which drives the generator and compressor and a cooling chamber. In this turbine, the air is compressed adiabatically (generally in rotary compressor) and then passed into the heating chamber. The compressed air is heated at constant pressure with the help of some external source, and made to flow over the turbine blades (generally reaction type). The gas, while flowing over the blades, gets expanded. From the turbine, the gas is passed through the cooling chamber where it is cooled at constant pressure with the help of circulating water, to its original temperature. Now the air is made to flow into the compressor again. It is thus obvious, that in a closed cycle gas turbine, the air is continuously circulated within the turbine.

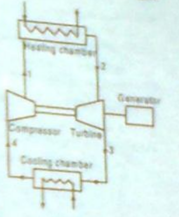
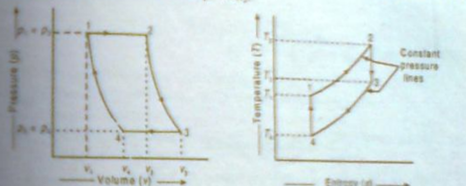


Fig. 5.14

Since the heating and cooling of air takes place at constant pressure, therefore this turbine is also called a constant pressure closed cycle gas turbine. It works on Joule's cycle as shown by p-v and T-s diagram in Fig. 5.15 (*a*) and (*b*) respectively.



(*a*) p-v diagram. (*b*) T-s diagram.

Fig. 5.15

The process 1-2 shows heating of the air in heating chamber at constant pressure. The process 2-3 shows isentropic expansion of air in the turbine. Similarly, the process 3-4 shows cooling of the air at constant pressure in cooling chamber. Finally, the process 4-1 shows isentropic compression of the air in the compressor.

5.29 Open Cycle Gas Turbine

An open cycle gas turbine, in its simplest form, as shown in Fig. 5.16, consists of a compressor, combustion chamber and a gas turbine which drives the generator and compressor.

In this turbine, the air is first sucked from the atmosphere and then compressed adiabatically (generally in a rotary compressor) and then passed into the combustion chamber. The compressed air is heated by the combustion of fuel and the products of combustion (*i.e.* hot gases formed by the combustion of fuel) also get mixed up with the com-

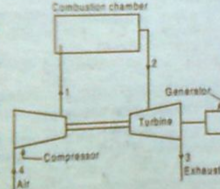


Fig. 5.16

pressed air, thus increasing the mass of compressed air. The hot gas is then made to flow over the turbine blades (generally reaction type). The gas, while flowing over the blades, gets expanded and finally exhausted into the atmosphere.

An open cycle gas turbine is also called continuous combustion gas turbine as the combustion of fuel takes pace continuously. This turbine also works on Joule's cycle.

5.30 Thermal Efficiency of Ideal Gas Turbine Plant

It is defined as the ratio of net work output obtained from the plant to the total heat supplied. The *p-v* and *T-s* diagram for an ideal gas turbine working on Joule cycle is shown in Fig 5.15.

We know that net work output obtained from the plant

$$= \text{Workdone by the turbine} - \text{Workdone by compressor}$$

$$= c_p\,(T_2 - T_3) - c_p\,(T_1 - T_4)$$

and heat supplied $= c_p\,(T_2 - T_1)$

$\therefore$ Thermal efficiency,

$$\eta_{th} = \frac{c_p\,(T_2 - T_3) - c_p\,(T_1 - T_4)}{c_p\,(T_2 - T_1)} = \frac{(T_2 - T_3) - (T_1 - T_4)}{T_2 - T_1} \quad ...(i)$$

We know that $$T_1 = T_4 \left(\frac{p_1}{p_4}\right)^{\frac{\gamma-1}{\gamma}} = T_4\,(r)^{\frac{\gamma-1}{\gamma}} \quad ...(ii)$$

and $$T_2 = T_3 \left(\frac{p_2}{p_3}\right)^{\frac{\gamma-1}{\gamma}} = T_3\,(r)^{\frac{\gamma-1}{\gamma}} \quad ...(iii)$$

where $$r = \frac{p_1}{p_4} = \frac{p_2}{p_3} = \text{Pressure ratio}$$

Substituting these values of T_1 and T_2 in equation (*i*), we get

$$\eta_{th} = 1 - \frac{1}{(r)^{\frac{\gamma-1}{\gamma}}}$$

Notes : 1. If the heat supplied is obtained from the mass of fuel × Calorific value, then the corresponding efficiency will be overall efficiency.

2. The ratio of the net work output obtained from the plant to the workdone by the turbine, is known as *work ratio* of the turbine plant. Mathematically,

$$\text{Work ratio} = \frac{\text{Net work output}}{\text{Work done by the turbine}} = \frac{c_p(T_2 - T_3) - c_p\,(T_1 - T_4)}{c_p(T_2 - T_3)}$$

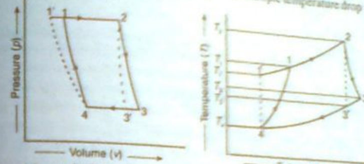
$$= 1 - \frac{T_1 - T_4}{T_2 - T_3} = 1 - \frac{T_4}{T_3}$$

...[Substituting the values of T_1 and T_2 from equations (*ii*) and (*iii*)]

5.31 Efficiency of Gas Turbine

It is defined as the ratio of workdone due to adiabatic expansion to the workdone due to isentropic expansion. In Fig. 5.17 (*a*) and (*b*), the cycle 1-2-3-4 represents the ideal cycle and 1'-2-3'-4 represents the actual cycle of a closed cycle gas turbine, in which the curve 4 – 1' shows the isentropic compression of air in the compressor and the curve 2 – 3' shows the isentropic expansion of air in the turbine. The turbine efficiency (also called adiabatic efficiency of turbine) is given by

$$\eta_t = \frac{c_p\,(T_2 - T_3)}{c_p\,(T_2 - T_{3'})} = \frac{T_2 - T_3}{T_2 - T_{3'}} = \frac{\text{Actual temperature drop}}{\text{Isentropic temperature drop}}$$



(*a*) *p-v* diagram. (*b*) *T-s* diagram.

Fig. 5.17

The compressor efficiency (also called isentropic efficiency of compressor) is the ratio of workdone due to isentropic compression to workdone due to adiabatic compression. Mathematically, compressor efficiency,

$$\eta_c = \frac{c_p\,(T_{1'} - T_4)}{c_p\,(T_1 - T_4)} = \frac{T_{1'} - T_4}{T_1 - T_4} = \frac{\text{Isentropic increase in temperature}}{\text{Actual increase in temperature}}$$

Notes : The efficiency of a simple gas turbine can be increased by using the following methods.

1. By compressing the air in two stages with an intercooler between the two.
2. By expanding the hot air in two stages with a reheater between the two.
3. By providing a heat exchanger through which hot gases from the turbine are made to pass which heat up the compressed air before entering the combustion chamber.

5.32 Fuels and Combustion

A fuel, may be defined as a substance (containing mostly carbon and hydrogen) which on burning with oxygen in the atmospheric air, produces a large amount of heat. The amount of heat generated is known as calorific value of the fuel. Since the principal constituents of a fuel are carbon and hydrogen, therefore, it is also known as hydrocarbon fuel. Sometimes, a few traces of sulphur are also present in it.

The fuels may be classified into the following three general forms :

1. Solid fuels, 2. Liquid fuels, and 3. Gaseous fuels.

Each of these fuels may be further subdivided into the following two types:

(*a*) Natural fuels, and (*b*) Prepared fuels.

5.33 Solid Fuels

The natural solid fuels are wood, peat, lignite or brown coal, bituminous coal and anthracite coal. The prepared solid fuels are wood charcoal, coke, briquetted coal and pulverised coal. These fuels are discussed, as follows:

1. *Wood.* It consists of mainly carbon and hydrogen. The wood is converted into coal when burnt in the absence of air. The average calorific value of wood is about 19 700 kJ / kg.

2. *Peat.* It may be regarded as the first stage in the formation of coal. Its average calorific value is 23 000 kJ / kg.

3. *Lignite or brown coal.* It represents the next stage of peat in the coal formation, and is an intermediate variety between bituminous coal and peat. Its average calorific value is 25 000 kJ / kg.

4. *Bituminous coal.* It represents the next stage of lignite in the coal formation and contains very little moisture (4 to 6 %) and 75 to 90 % of carbon. The average calorific value of bituminous coal is 33 500 kJ / kg.

5. *Anthracite coal.* It represents the final stage in the coal formation, and contains 90% or more carbon with a very little volatile matter. It possesses a high calorific value of about 36 000 kJ / kg and is, therefore, very valuable for steam raising and general power purposes.

6. *Wood charcoal.* It is made by heating wood with a limited supply of air to a temperature not less than 280° C. It is a good prepared solid fuel, and is used for various metallurgical processes.

7. *Coke.* It is produced when coal is strongly heated continuously for 42 to 48 hours in the absence of air in a closed vessel. This process is known as *carbonisation of coal.* Coke is dull black in colour, porous and smokeless. It has a high carbon content (85 to 90%) and has a higher calorific value than coal.

If the carbonisation of coal is carried out at 500 to 700°C, the resulting coke is called *lower temperature coke* or *soft coke.* It is used as a domestic fuel. The coke produced by carbonisation of coal at 900 to 1100°C, is known as *hard coke.* The hard coke is mostly used as a blast furnace fuel for extracting pig iron from iron ores, and to some extent as a fuel in cupola furnace for producing cast iron.

8. *Briquetted coal.* It is produced from the finely ground coal by moulding under pressure with or without a binding material. The briquetted coal has the advantage of having, practically, no loss of fuel through grate openings and thus it increases the heating value of the fuel.

9. *Pulverised coal.* The low grade coal with a high ash content, is powdered to produce pulverised coal. The coal is first dried and then crushed into a fine powder by pulverising machines. The pulverised coal is widely used in the cement industry and also in metallurgical processes.

5.34 Liquid Fuels

Almost all the commercial liquid fuels are derived from natural petroleum (or crude oil). The liquid fuels consist of hydrocarbons. The natural petroleum may be separated into petrol or gasoline, paraffin oil or kerosene, fuel oils and lubricating oils by boiling the crude oil at different temperatures and subsequent fractional distillation or by a process such as cracking. The solid products like vaseline and paraffin wax are recovered from the residue in the still.

The following are some important liquid fuels :

1. *Petrol or gasoline.* It is the lightest and most volatile liquid fuel, mainly used for light petrol engines. It is distilled at a temperature from 65° to 220° C.

2. *Kerosene or paraffin oil.* It is heavier and less volatile fuel than the petrol, and is used as heating and lighting fuel. It is distilled at a temperature from 220° to 345° C.

3. *Heavy fuel oils.* The liquid fuels distilled after petrol and kerosene are known as heavy fuel oils. These oils are used in diesel engines and in oil-fired boilers. These are distilled at temperature from 345° C to 470° C.

5.35 Gaseous Fuels

The natural gas is, usually, found in or near the petroleum fields, under the earth's surface. It, essentially consists of marsh gas or methane (CH_4) together with small amounts of other gases such as ethane (C_2H_6), carbon dioxide (CO_2) and carbon monoxide (CO). The following prepared gases, which are used as fuels, are important:

1. *Coal gas.* It is also known as a town gas. It is obtained by the carbonisation of coal and consists mainly of hydrogen, carbon monoxide and various hydrocarbons. It is very rich among combustible gases, and is largely used in towns for street and domestic lighting and heating. It is also used in furnaces and for running gas engines. Its calorific value is about 21 000 to 25 000 kJ / m^3.

2. *Producer gas.* It is obtained by the partial combustion of coal, coke, anthracite coal or charcoal in a mixed air-steam blast. It is, mostly, used for furnaces particularly for glass melting and also for power generation. Its manufacturing cost is low, and has a calorific value of about 5000 to 6700 kJ / m^3.

3. *Water gas.* It is a mixture of hydrogen and carbon monoxide and is made by passing steam over incandescent coke. As it burns with a blue flame, it is also known as blue water gas.

The water gas is usually converted into carburetted (enriched) water gas by passing it through a carburetter into which a gas oil is sprayed. It is, usually, mixed with coal gas to form town gas. The water gas is used in furnaces and for welding.

4. *Mond gas.* It is produced by passing air and a large amount of steam over waste coal at about 650° C. It is used for power generation and heating. It is also suitable for use in gas engines. Its calorific value is about 5850 kJ / m^3.

5. *Blast furnace gas.* It is a by-product in the production of pig iron in the blast furnace. This gas serves as a fuel in steel works, for power generation in gas engines, for steam raising in boilers and for preheating the blast for furnace. It is extensively used as fuel for metallurgical furnaces. The gas, leaving the blast furnace, has a high dust content, the proportion of which varies with the operation of the furnace. It has a low heating value of about 3750 kJ / m^3.

6. *Coke oven gas.* It is a by-product from coke oven, and is obtained by the carbonisation of bituminous coal. Its calorific value varies from 14 500 to 18 500 kJ / m^3. It is used for industrial heating and power generation.

5.36 Calorific Value of Fuels

The calorific value (briefly written as C. V.) or heat value of a solid or liquid fuel may be defined as the amount of heat given out by the complete combustion of 1 kg of fuel. It is expressed in terms of kJ / kg of fuel. The calorific value of gaseous fuels is, however, expressed in terms of kJ / m^3 at a specified temperature and pressure.

Following are the two types of the calorific value of fuels:

1. *Gross or higher calorific value.* The amount of heat obtained by the complete combustion of 1 kg of a fuel, when the products of its combustion are cooled down to the temperature of supplied air (usually taken as 15° C), is called the *gross or higher calorific value of fuel.* If the chemical analysis of a fuel is available, then the higher calorific value of the fuel is determined by the following formula, known as Dulong's formula:

$$\text{H. C. V.} = 33\,800\,C + 144\,000\,H_2 + 9270\,S \text{ kJ / kg}$$

where C, H_2 and S represent the mass of carbon, hydrogen and sulphur in 1 kg of fuel, and the numerical values indicate their respective calorific values.

If the fuel contains oxygen (O_2), then it is assumed that the whole amount is combined with hydrogen having mass equal to 1 / 8th of that of oxygen. Therefore, while finding the calorific value of fuel, this amount of hydrogen should be subtracted.

$$\therefore \quad \text{H.C.V.} = 33\,800\,C + 144\,000\left(H_2 - \frac{O_2}{8}\right) + 9270\,S \text{ kJ/kg}$$

2. *Net or lower calorific value.* When the heat absorbed or carried away by the products of combustion is not recovered (which is the case in actual practice), and the steam formed during

combustion is not condensed, then the amount of heat obtained per kg of the fuel is known as *net or lower calorific value*. It is briefly written as L. C. V.

If the higher calorific value is known, then the lower calorific value may be obtained by subtracting the amont of heat carried away by products of combustion (especially steam) from H. C. V.

$$\therefore \quad \text{L. C. V.} = \text{H. C. V.} - \text{Heat of steam formed during combustion}$$

Notes : 1. The calorific value of a solid and liquid fuels may be found by using bomb calorimeter.

2. The calorific value of gaseous and liquid fuels may be found by using any gas calorimeter like Boy's gas calorimeter or Junker's gas calorimeter.

5.37 Combustion of Fuels

The combustion of fuels may be defined as a chemical combination of oxygen, in the atmospheric air, and hydro-carbons. The following chemical equations for the chemical combination of oxygen (representing combustion) are important :

1. When carbon burns in sufficient quantity of oxygen, carbon dioxide is produced along with a release of large amount of heat. This is represented by the following chemical equation :

$$C + O_2 = CO_2$$

$$1 \text{ mol.} + 1 \text{ mol.} = 1 \text{ mol.} \qquad \text{...(By volume)}$$

or $$12 \text{ kg} + 32 \text{ kg} = 44 \text{ kg} \qquad \text{...(By mass)}$$

i.e. $$1 \text{ kg} + \frac{8}{3} \text{ kg} = \frac{11}{3} \text{ kg}$$

It means that 1 kg of carbon requires 8 / 3 kg of oxygen for its complete combustion, and produces 11 / 3 kg of carbon dioxide gas.

2. If sufficient oxygen is not available, then combustion of carbon is incomplete. It then produces carbon monoxide instead of carbon dioxide. It is represented by the following chemical equation:

$$2C + O_2 = 2CO$$

$$2 \text{ mol.} + 1 \text{ mol.} = 2 \text{ mol.} \qquad \text{...(By volume)}$$

or $$2 \times 12 \text{ kg} + 2 \times 16 \text{ kg} = 2 \times 28 \text{ kg} \qquad \text{...(By mass)}$$

i.e. $$1 \text{kg} + \frac{4}{3} \text{ kg} = \frac{7}{3} \text{kg}$$

It means that 1 kg of carbon requires 4 / 3 kg of oxygen, and produces 7 / 3 kg of carbon monoxide.

3. If carbon monoxide is burnt further, it is converted into carbon dioxide. Thus

$$2CO + O_2 = 2CO_2$$

$$2 \text{ mol.} + 1 \text{ mol.} = 2 \text{ mol.} \qquad \text{...(By volume)}$$

or $$2 \times 28 \text{ kg} + 2 \times 16 \text{ kg} = 2 \times 44 \text{ kg} \qquad \text{...(By mass)}$$

i.e. $$1 \text{kg} + \frac{4}{7} \text{ kg} = \frac{11}{7} \text{ kg}$$

It means that 1 kg of carbon monoxide requires 4 / 7 kg of oxygen, and produces 11 / 7 kg of carbon dioxide.

4. When sulphur burns with oxygen, it produces sulphur dioxide. This is represented by the following chemical equation :

$$S + O_2 = SO_2$$

$$1 \text{ mol.} + 1 \text{ mol.} = 1 \text{ mol.}$$

or $$32 \text{ kg} + 2 \times 16 \text{ kg} = 64 \text{ kg} \qquad \text{...(By volume)}$$

i.e. $$1 \text{ kg} + 1 \text{ kg} = 2 \text{ kg} \qquad \text{...(By mass)}$$

It means that 1 kg of sulphur requires 1 kg of oxygen for complete combustion to produce 2 kg of sulphur dioxide.

5. $$2H_2 + O_2 = 2H_2O$$

or $$\begin{bmatrix} 2 \text{ Vol.} + 1 \text{ Vol.} = 2 \text{ Vol.} \\ 2 m^3 + 1 m^3 = 2 m^3 \end{bmatrix} \qquad \text{...(By volume)}$$

i.e. $$\begin{bmatrix} 2 \times 2 \text{ kg} + 1 \times 32 \text{ kg} = 2 \times 18 \text{ kg} \\ 1 \text{ kg} + 8 \text{ kg} = 9 \text{ kg} \end{bmatrix} \qquad \text{...(By mass)}$$

It means that 2 volumes of hydrogen require 1 volume of oxygen to produce 2 volumes of water or steam.

Or in other words, 1 kg of hydrogen requires 8 kg of oxygen and produces 9 kg of water or steam.

6. $$CH_4 + 2O_2 = CO_2 + 2H_2O$$

or $$\begin{bmatrix} 1 \text{ Vol.} + 2 \text{ Vol.} = 1 \text{ Vol.} + 2 \text{ Vol.} \\ 1 m^3 + 2 m^3 = 1 m^3 + 2 m^2 \end{bmatrix} \qquad \text{...(By volume)}$$

i.e. $$\begin{bmatrix} 16 \text{ kg} + 2 \times 32 \text{ kg} = 44 \text{ kg} + 2 \times 18 \text{ kg} \\ 1 \text{ kg} + 4 \text{ kg} = \frac{11}{4} \text{ kg} + \frac{9}{4} \text{ kg} \end{bmatrix}$$

It means that 1 volume of methane requires 2 volumes of oxygen and produces 1 volume of carbon dioxide and 2 volumes of water or steam.

Or in other words, 1 kg of methane requires 4 kg of oxygen and produces 11 / 4 kg of carbon dioxide and 9 / 4 kg of water or steam.

7. $$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O$$

or $$\begin{bmatrix} 1 \text{ Vol.} + 3 \text{ Vol.} = 2 \text{ Vol.} + 2 \text{ Vol.} \\ 1 m^3 + 3 m^3 = 2 m^3 + 2 m^3 \end{bmatrix} \qquad \text{...(By volume)}$$

i.e. $$\begin{bmatrix} 28 \text{ kg} + 3 \times 32 \text{ kg} = 2 \times 44 \text{ kg} + 2 \times 18 \text{ kg} \\ 1 \text{ kg} + \frac{24}{7} \text{ kg} = \frac{22}{7} \text{ kg} + \frac{9}{7} \text{ kg} \end{bmatrix} \qquad \text{...(By mass)}$$

It means that 1 volume of ethylene requires 3 volumes of oxygen and produces 2 volumes of carbon dioxide and 2 volumes of water or steam.

Or in other words, 1 kg of ethylene requires 24 / 7 kg of oxygen and produces 22 / 7 kg of carbon dioxide and 9 / 7 kg of water or steam.

5.38 Theoretical or Minimum Air Required for Complete Combustion

In order to obtain maximum amount of heat from a fuel, the adequate supply of oxygen is very essential for the complete combustion of a fuel.

The theoretical or minimum mass (or volume) of oxygen required for complete combustion of 1 kg of fuel may be calculated from the chemical analysis of the fuel. The mass of oxygen, required by each of the constituents of the fuel, may be calculated from the chemical equations in Art. 5.37. Now consider 1 kg of a fuel.

We know that 1 kg of carbon requires 8 / 3 kg of oxygen for its complete combustion. Similarly, 1 kg of hydrogen requires 8 kg of oxygen and 1 kg of sulphur requires 1 kg of oxygen for its complete combustion.

∴ Total oxygen required for complete combustion of 1 kg of fuel

$$= \frac{8}{3}C + 8H_2 + S \text{ kg} \qquad \text{...}(i)$$

If some oxygen (say O_2 kg) is already present in the fuel, then total oxygen required for the complete combustion of 1 kg of fuel

$$= \left[\frac{8}{3}C + 8H_2 + S\right] - O_2 \text{ kg} \qquad \text{...}(ii)$$

It may be noted that the oxygen has to be obtained from the atmospheric air, which mainly consists of nitrogen and oxygen.

The composition of air is taken as:

$$\text{Nitrogen } (N_2) = 77\,\%\text{ ; Oxygen } (O_2) = 23\% \qquad \text{...(By mass)}$$

and

$$\text{Nitrogen } (N_2) = 79\%\text{; Oxygen } (O_2) = 21\% \qquad \text{...(By volume)}$$

It is thus obvious, that for obtaining 1 kg of oxygen, amount of air required

$$= \frac{100}{23} = 4.35 \text{ kg} \qquad \text{...(By mass)}$$

∴ Theoretical or minimum air required for complete combustion of 1 kg of fuel

$$= \frac{100}{23}\left[\left(\frac{8}{3}C + 8H_2 + S\right) - O_2\right] \text{kg}$$

5.39 Mass of Carbon in Flue Gases

The mass of carbon, contained in 1 kg of flue or exhaust gases, may be calculated from the mass of carbon dioxide and carbon monoxide present in them.

We know that 1 kg of carbon produces 11 / 3 kg of carbon dioxide. Hence 1 kg of carbon dioxide will contain 3 / 11 kg of carbon. Also 1 kg of carbon produces 7 / 3 kg of carbon monoxide, hence 1 kg of carbon monoxide will contain 3 / 7 kg of carbon.

∴ Mass of carbon per kg of flue gas

$$= \frac{3}{11}CO_2 + \frac{3}{7}CO$$

5.40 Mass of Excess Air Supplied

In order to ensure complete and rapid combustion of fuel, some quantity of air, in excess of the

theoretical or minimum air, is supplied. We know that in order to supply one kg of oxygen, we need 100 / 23 of air. Similarly, the mass of excess air supplied

$$= \frac{100}{23} \times \text{Mass of excess oxygen}$$

OBJECTIVE TYPE QUESTIONS

1. A definite area or a space where some thermodynamic process takes place is known as
   (a) thermodynamic system (b) thermodynamic cycle
   (c) thermodynamic process (d) thermodynamic law
2. A closed system is one in which heat and work crosses the boundary of the system but the mass of the working substance does not crosses the boundary of the system.
   (a) Yes (b) No
3. An open system is one in which
   (a) heat and work crosses the boundary of the system, but the mass of the working substance does not crosses the boundary of the system
   (b) mass of the working substance crosses the boundary of the system but the heat and work does not crosses the boundary of the system
   (c) both the heat and work as well as mass of the working substance crosses the boundary of the system
   (d) neither the heat and work nor the mass of the working substance crosses the boundary of the system
4. In an isolated system, neither the heat and work nor the mass of the working substance crosses the boundary of the system.
   (a) True (b) False
5. In an extensive property of a thermodynamic system
   (a) extensive heat is transferred (b) extensive work is done
   (c) extensive energy is utilised (d) none of these
6. The thermodynamic property of a system is said to be an intensive property whose value for the entire system .... the sum of their value for the individual parts of the system.
   (a) is equal to (b) is not equal to
7. The property of the system, whose value for the entire system is equal to the sum of their values for the individual parts of the system is called extensive property
   (a) Yes (b) No
8. Which of the following is the extensive property of a thermodynamic system?
   (a) Pressure (b) Volume (c) Temperature (d) Density
9. Which of the following is an intensive property of a thermodynamic system?
   (a) Volume (b) Temperature (c) Mass (d) Energy
10. The specific volume of a system is an .... property.
    (a) extensive (b) intensive
11. The absolute zero temperature is taken as
    (a) −273°C (b) 273°C (c) 237°C (d) −237°C

6

Steam Boilers and Engines

6.1 Introduction

A steam generator or boiler is, usually, a closed vessel made of steel. Its function is to transfer the heat produced by the combustion of fuel (solid, liquid or gaseous) to water, and ultimately to generate steam. The selection of type and size of a steam boiler depends upon the following factors:

1. The power required and the working pressure.
2. The geographical position of the power house.
3. The fuel and water available.
4. The probable permanency of the station.
5. The probable load factor.

6.2 Classification of Steam Boilers

Though there are many classifications of steam boilers, yet the following are important from the subject point of view:

1. *According to the contents in the tube*

   (*a*) Fire tube or smoke tube, and (*b*) Water tube.

In *fire tube steam boilers*, the flames and hot gases, produced by combustion of fuel, pass through the tubes (called multi-tubes) which are surrounded by water. Examples of fire tube steam boilers are: Simple vertical boiler, Cochran boiler, Lancashire boiler, Cornish boiler, Scotch marine boiler, Locomotive boiler, and Velcon boiler.

In *water tube steam boilers*, the water is contained inside the tubes (called water tubes) which are surrounded by flames and hot gases from outside. Examples of water tube boilers are : Babcock and Wilcox boiler, Stirling boiler, La-Mont boiler, Benson boiler, Yarrow boiler and Loeffler boiler.

2. *According to the position of the furnace*

   (*a*) Internally fired, and (*b*) Externally fired.

In *internally fired steam boilers*, the furnace is located inside the boiler shell. Most of the fire tube steam boilers are internally fired.

In *externally fired steam boilers*, the furnace is arranged underneath in a brick-work setting. Water tube steam boilers are always externally fired.

3. *According to the axis of the shell*

   (*a*) Vertical, and (*b*) Horizontal.

In *vertical steam boilers*, the axis of the shell is vertical, whereas it is horizontal in case of *horizontal steam boilers*.

4. *According to the number of tubes*

   (*a*) Single tube, and (*b*) Multitubular.

In *single tube steam boilers*, there is only one fire tube or water tube. Simple vertical boiler and Cornish boilers are single tube boilers.

In *multitubular steam boilers*, there are two or more fire tubes or water tubes.

5. *According to the method of circulation of water and steam*

   (*a*) Natural circulation, and (*b*) Forced circulation.

In *natural circulation steam boilers*, the circulation of water is by natural convection currents which are set up during the heating of water. In most of the steam boilers, there is a natural circulation of water.

In *forced circulation steam boilers*, there is a forced circulation of water by a centrifugal pump driven by some external power. Use of forced circulation is made in high pressure boilers such as La-Mont boiler, Benson boiler, Loeffler boiler and Velcon boiler.

6. *According to the use*

   (*a*) Stationary, and (*b*) Mobile.

The *stationary steam boilers* are used in power plants, and in industrial process work. These are called stationary because they do not move from one place to another.

The *mobile steam boilers* are those which move from one place to another. These boilers are locomotive and marine boilers.

7. *According to the source of heat*

The steam boilers may also be classified according to the source of heat supplied for producing steam. These sources may be the combustion of solid, liquid or gaseous fuel, hot waste gases as by-products of other chemical processes, electrical energy or nuclear energy, etc.

6.3 Simple Vertical Boiler

A simple vertical boiler produces steam at a low pressure and in small quantities. It is, therefore, used for low power generation or at places where space is limited. This boiler has a cylindrical shell surrounding a nearly cylindrical fire box. The fire box is slightly tapered towards the top to allow the ready passage of the steam to the surface. The fire box is fitted with two or more inclined cross tubes, to increase the heating surface as well as to improve the circulation of water.

6.4 Cochran Boiler or Vertical Multitubular Boiler

There are various designs of vertical multitubular boilers. A Cochran boiler is considered to be one of the most efficient type of such boilers. It is an improved type of simple vertical boiler.

This boiler consists of an external cylindrical shell and a fire box. The shell and fire box are both hemispherical. The hemispherical crown of the boiler shell gives maximum space and strength to withstand the pressure of steam inside the boiler. The hemispherical crown of the fire box is also advantageous for resisting intense heat. The fire box and the combustion chamber is connected through a short pipe. The flue gases from the combustion chamber flow to the smoke box through a number of smoke tubes. These tubes generally have 62.5 mm external diameter and are 165 in number. The gases from the smoke box pass to the atmosphere through a chimney. The combustion chamber is lined with fire bricks on the shell side. A manhole near the top of the crown on the shell is provided for cleaning.

6.5 Scotch Marine Boiler

The marine steam boilers of the scotch or tank type are used for marine works, particularly, due to their compactness, efficiency in operation and their ability to use any type of water. It does not require brick work setting and external flues.

It has a drum of diameter from 2.5 to 3.5 metres placed horizontally. These steam boilers may be *single ended* or *double ended*. The length of a single ended steam boiler may be upto 3.5 metres while for double ended upto 6.5 metres. A single ended boiler has one to four furnaces which enter from front end of the boiler. A double ended boiler has furnaces on both of its ends, and may have furnaces from two to four in each end.

6.6 Lancashire Boiler

It is a stationary fire tube type, internally fired, horizontal and natural circulation boiler. It is used where working pressure and power required are moderate. These boilers have a cylindrical shell of 1.75 m to 2.75 m diameter. Its length varies from 7.25 m to 9 m. It has two internal flue tubes having diameter about 0.4 times that of shell. This type of boiler is set in brick work forming external flue so that part of the heating surface is on the external shell.

6.7 Cornish Boiler

It is similar to Lancashire boiler in all respects, except there is only one flue tube in Cornish boiler instead of two in Lancashire boiler. The diameter of Cornish boiler is generally 1 m to 2 m and its length varies from 5 m to 7.5 m. The diameter of flue tube may be about 0.6 times that of shell. The capacity and working pressure of a Cornish boiler is low as compared to Lancashire boiler.

6.8 Locomotive Boiler

It is a multi-tubular horizontal, internally fired and mobile boiler. The principle feature of this boiler is to produce steam at a very high rate.

It consists of a shell or barrel having 1.5 metre diameter and 4 metres in length. The coal is fed into the fire box through the fire door and burns on grate. The flue gases from the grate are deflected by a brick arch, and thus whole of the fire box is properly heated. There are about 157 thin tubes or fire tubes (47.5 mm diameter) and 24 thick or superheated tubes (130 mm diameter). The flue gases after passing through these tubes enter a smoke box. The gases are then lead to atmosphere through a chimney. The barrel contains water around the tubes, which is heated up by the flue gases and gets converted into steam.

6.9 Babcock and Wilcox Boiler

It is a straight tube, stationary type water tube boiler. In this boiler, the water tubes are inclined to the horizontal and connects the uptake header to the downtake header. Each row of the tubes is connected with two headers and there are plenty of such rows.

6.10 La-Mont Boiler

This is a modern high pressure water tube type steam boiler working on a forced circulation. The circulation is maintained by a centrifugal pump, driven by a steam turbine, using steam from the boiler. The forced circulation causes the feed water to circulate through the water walls and drums equal to ten times the mass of steam evaporated. This prevents the tubes from being overheated.

6.11 Boiler Mountings

These are the fittings, which are mounted on the boiler for its proper and safe functioning. Some of the important boiler mountings are as follows:

1. *Water level indicator.* It is an important fitting, which indicates the water level inside the boiler to an observer. It is a safety device, upon which the correct working of the boiler depends. This fitting may be seen in front of the boiler, and are generally two in number.

2. *Pressure gauge.* A pressure gauge is used to measure the pressure of the steam inside the steam boiler. It is fixed in front of the steam boiler. The pressure gauges generally used are of Bourden type.

3. *Safety valves.* These are attached to the steam chest for preventing explosions due to excessive internal pressure of steam. A steam boiler is, usually, provided with two safety valves. These are directly placed on the boiler. In brief, the function of a safety valve is to blow off the steam when the pressure of steam inside the boiler exceeds the working pressure. The following are the four types of safety valves :

(*a*) Lever safety valve,

(*b*) Dead weight safety valve,

(*c*) High steam and low water safety valve, and

(*d*) Spring loaded safety valve.

It may be noted that the first three types of the safety valves are usually empoyed with stationary boilers. But the fourth type is mainly used for locomotive and marine boilers.

4. *Steam stop valve.* It is the largest valve on the steam boiler. It is, usually, fitted to the highest part of the shell by means of a flange. The principal functions of a stop valve are :

(*a*) To control the flow of steam from the boiler to the main steam pipe.

(*b*) To shut off the steam completely when required.

5. *Blow-off-cock.* The principal functions of a blow-off cock are :

(*a*) To empty the boiler whenever required.

(*b*) To discharge the mud, scale or sediments which are accumulated at the bottom of the boiler.

6. *Feed check valve.* It is a non-return valve, fitted to a screwed spindle to regulate the lift. Its function is to regulate the supply of water, which is pumped into the boiler, by the feed pump. This valve must have its spindle lifted before the pump is started. It is fitted to the shell slightly below the normal water level of the boiler.

7. *Fusible plug.* It is fitted to the crown plate to the furnace or the fire. Its object is to put off the fire in the furnace of the boiler when the level of water in the boiler falls to an unsafe limit, and thus avoids the explosion which may take place due to overheating of the furnace plate.

6.12 Boiler Accessories

These are the devices which are used as integral parts of a boiler and help in running efficiently. Some of the important boiler accessories are as follows:

1. *Feed pump.* It is used to deliver water to the boiler. A feed pump may be of centrifugal type or reciprocating type. But a double acting reciprocating pump is commonly used as a feed pump these days.

2. *Superheater.* It is an important device of a steam generating unit. Its purpose is to increase the temperature of saturated steam without raising its pressure. It is generally an integral part of a boiler, and is placed in the path of hot flue gases from the furnace. The heat, given up by these flue gases, is used in superheating the steam. Such superheaters, which are installed within the boiler, are known as integral superheaters.

3. *Economiser.* It is a device used to heat feed water by utilising the heat in the exhaust flue gases before leaving through the chimney. It improves the economy of the steam boiler. Following are the advantages of using an economiser :

(*a*) There is about 15 to 20% of coal saving.

(*b*) It increases the steam raising capacity of a boiler because it shortens the time required to convert water into steam.

(c) It prevents formation of scale in boiler water tubes, because the scale formed in the economiser tubes can be cleaned easily.

(d) Since the feed water entering the boiler is hot, therefore strains due to unequal expansion are minimised.

6.13 Boiler Performance

The performance of a steam boiler is measured is terms of its evaporative capacity. The *evaporative capacity* of a boiler is the amount of water evaporated or steam produced in kg / h. It may also be expressed in kg / kg of fuel burnt or kg / h / m^2 of heating surface.

6.14 Equivalent Evaporation

It is the amount of water evaporated from feed water at 100° C and formed into dry and saturated steam at 100°C at normal atmospheric pressure (1.01 bar). It is, usually, written as "from and at 100° C".

As the water is already at the boiling temperature, it requires only latent heat at normal atmospheric pressure, to convert it into steam at temperature 100° C. The value of this latent heat is taken as 2257 kJ / kg. Mathematically, equivalent evaporation "from and at 100° C",

$$E = \frac{m_e\,(h - h_{f1})}{2257}$$

where m_e = Mass of water actually evaporated or steam produced in kg / h or kg / kg of fuel burnt,

h = Total heat of steam in kJ / kg of steam, and

h_{f1} = Sensible heat of feed water in kJ / kg of steam.

Note : The factor $\dfrac{h - h_{f1}}{2257}$ is known as *factor of evaporation* and it is always greater than unity for all boilers.

6.15 Boiler Efficiency

It may be defined as the ratio of heat actually used in producing the steam to the heat liberated in the furnace. It is also known as thermal efficiency of the boiler. Mathematically, boiler efficiency or thermal efficiency,

$$\eta = \frac{\text{Heat actually used in producing steam}}{\text{Heat liberated in the furnace}} = \frac{m_e\,(h - h_{f1})}{C}$$

where m_e = Mass of water actually evaporated or actual evaporation in kg / kg of fuel, and

C = Calorific value of fuel in kJ / kg of fuel.

Notes : 1. Let m_s = Total mass of water evaporated into steam in kg, and

m_f = Mass of fuel in kg.

$\therefore \quad m_e = m_s / m_f$

and

$$\eta = \frac{m_s\,(h - h_{f1})}{m_f \times C}$$

2. If a boiler consisting of an economiser and superheater is considered to be a single unit, then the efficiency is termed as overall efficiency of the boiler.

6.16 Boiler Trial

The main objects of a boiler trial are :

1. To determine the generating capacity of the boiler.
2. To determine the thermal efficiency of the boiler when working at a definite pressure.
3. To prepare heat balance sheet for the boiler.

6.17 Heat Losses in a Boiler

Following are the heat losses in a boiler :

1. Heat lost to dry flue gases.
2. Heat lost to moisture present in the fuel.
3. Heat lost to steam formed by combustion of hydrogen.
4. Heat lost due to unburnt carbon in ashpit.
5. Heat lost to incomplete combustion of carbon to carbon monoxide.
6. Heat lost due to radiation, etc.

6.18 Boiler Draught

It is the difference of pressures above and below the fire grate. The main objects of producing draught in a boiler are :

1. To provide an adequate supply of air for the fuel combustion.
2. To exhaust the gases of combustion from the combustion chamber.
3. To discharge these gases to the atmosphere through the chimney.

The draughts may be of the following two types :

1. *Natural draught.* It is the draught produced by a chimney due to the difference of densities between the hot gases inside the chimney and cold atmospheric air outside it. It is also called chimney draught.

2. *Mechanical (or artificial) draught.* It is the draught produced by a fan, blower or steam jet. In general, the mechanical draught is provided, when natural draught is not sufficient. It may be induced or forced.

Note : When a fan (generally of the centrifugal type) is placed in the path of the flue gases before they enter the chimney, the draught produced is known as *induced fan draught*. On the other hand, when the fan is placed before the grate and the air is forced into the grate through the closed ash pit, the draught produced is then known as *forced fan draught*. Similarly, when the steam jet issuing from a nozzle is placed in the chimney, it is known as *induced steam jet draught*. When the steam jet issuing from a nozzle is placed in the ash pit under the fire grate of the furnace, it is then known as *forced steam jet draught*.

6.19 Height of Chimney

We have already discussed that the natural draught is produced by means of a chimney. Since the amount of draught depends upon the height of chimney, therefore its height should be such that it can produce a sufficient draught.

We know that the draught pressure is due to the pressure difference between the hot column of gas in the chimney and a similar column of cold air outside the chimney. It is usually expressed in mm of water. Mathematically, draught pressure,

$$p = 353\,H\left(\frac{1}{T_1} - \frac{m+1}{m\,T_2}\right) \text{ mm of water}$$

where H = Height of the chimney above the fire grate in metres,

m = Mass of air actually used in kg / kg of fuel,

T_1 = Absolute temperature of air outside the chimney in K, and

T_2 = Absolute temperature of the flue gas inside the chimney in K.

Notes : 1. The above equation gives only the theoretical value of the draught and is known as *static draught*.

2. The draught may also be expressed in terms of column of hot gases. If H' is the height in metres of the hot gas column which would produce the draught pressure p, then

$$p = \frac{353(m+1)}{m.T_2} \times H'$$

where

$$H' = H\left[\left(\frac{m}{m+1} \times \frac{T_2}{T_1}\right) - 1\right] \text{ metres}$$

3. The velocity of flue gases through the chimney under a static draught of H' metres is given by

$$v = \sqrt{2gH'} = 4.43\sqrt{H'}$$

4. For maximum discharge, the height of hot gas column producing the draught is equal to the height of the chimney, *i.e.* $H' = H$.

5. The draught pressure for maximum discharge is given by

$$p = \frac{176.5H}{T_1} \text{ mm of water}$$

6.20 Steam Engines

In all steam engines, the steam is used as the working substance. These engines operate on the principle of First Law of Thermodynamics, *i.e.* heat and work are mutually convertible. In a steam engine, as the heat energy in the steam is converted into mechanical work by the reciprocating (to and fro) motion of the piston, it is also called *reciprocating steam engine*. Moreover, as the combustion of the fuel takes place outside the engine cylinder, it is also called an *external combustion engine*.

6.21 Classification of Steam Engines

The steam engines are classified as discussed below:

1. *According to the number of working strokes*

(*a*) Single acting steam engine, and (*b*) Double acting steam engine.

When steam is admitted on one side of the piston, and one working stroke is produced during each revolution of the crankshaft, it is said to be a *single acting steam engine*. But when the steam is admitted, in turn, on both sides of the piston and two working strokes are produced during each revolution of the crankshaft, it is said to be a *double acting steam engine*. A double acting steam engine produces double the power than that produced by a single acting steam engine.

2. *According to position of the cylinder*

(*a*) Horizontal steam engine, and (*b*) Vertical steam engine.

When the axis of the cylinder is horizontal, it is said to be a *horizontal steam engine*. But when axis of the cylinder is vertical, it is called *vertical steam engine*. A vertical steam engine requires less floor area than the horizontal steam engine.

3. *According to the speed of the crankshaft*

(*a*) Slow speed steam engine (*b*) Medium speed steam engine, and

(*c*) High speed steam engine.

When the speed of the crankshaft is less than 100 revolutions per minute (r.p.m.), it is called a *slow speed steam engine*. But when the speed of the crankshaft is between 100 r.p.m. and 250 r.p.m., it is called a *medium speed steam engine*. Similarly, when the speed of the crankshaft is above 250 r.p.m., it is known as a *high speed steam engine*.

4. *According to the type of exhaust*

(*a*) Condensing steam engine, and (*b*) Non-condensing steam engine.

When steam after doing work in the cylinder passes into a condenser, which condenses the steam into water at a pressure less than the atmospheric pressure, it is said to be a *condensing steam engine*. But when the steam after doing work in the cylinder is exhausted into the atmosphere, it is said to be a *non condensing steam engine*. The steam pressure in the cylinder is, therefore, not allowed to fall below the atmospheric pressure.

5. *According to expansion of the steam in the engine cylinder*

(*a*) Simple steam engine, and (*b*) Compound steam engine.

When expansion of the steam is carried out in a single cylinder and then exhausted into the atmosphere or a condenser, it is said to be a *simple steam engine*. But when the expansion of the steam is completed in two or more cylinders, the engine is called a *compound steam engine*. The compound steam engines are generally condensing engines. But some of them may be non-condensing also.

6. *According to the method of governing employed*

(*a*) Throttling steam engine, and (*b*) Automatic cut off steam engine.

When the engine speed is controlled by means of a throttle valve in the steam pipe, which regulates the pressure of steam to the engine, it is called a *throttling steam engine*. But when the speed is controlled by controlling the steam pressure with an automatic cut-off governor, it is called an *automatic cut-off steam engine*.

6.22 Important Parts of a Steam Engine

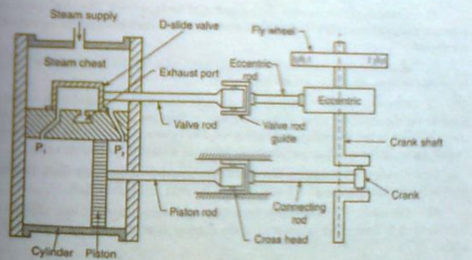


Fig. 6.1

Fig. 6.1 shows a single cylinder, double acting, horizontal reciprocating steam engine. The important parts of a steam engine are discussed as below :

1. *Frame.* It is a heavy cast iron part which supports all the stationary as well as moving parts and holds them in proper position. It, generally, rests on engine foundations.

2. *Cylinder.* It is also a cast iron cylindrical hollow vessel, in which the piston moves to and fro under the steam pressure. Both ends of the cylinder are closed and made steam tight. In small steam engines, the cylinder is made an integral part of the frame.

3. *Steam chest.* It is casted as an integral part of the cylinder. The superheated steam at a high pressure (above 20 atmospheres) from the boiler is fed into the steam chest and it then supplies to the cylinder with the movement of D-slide valve.

4. *D-slide valve.* It moves in the steam chest with simple harmonic motion. Its function is to exhaust steam from the cylinder at proper moment.

5. *Inlet and exhaust ports.* These are holes provided in the body of the cylinder for the movement of steam. The steam is admitted from the steam chest alternately to either sides of the cylinder through the inlet ports, P_1 and P_2. The steam after doing its work in the cylinder, is exhausted through the exhaust port.

6. *Piston.* It is a cylindrical disc, moving to and fro, in the cylinder because of the steam pressure. Its function is to convert heat energy of the steam into mechanical work. Piston rings, made from cast iron, are fitted in the grooves in the piston. Their purpose is to prevent the leakage of steam.

7. *Piston rod.* It is a circular rod, which is connected to the piston on one side and cross-head to the other. Its main function is to transfer motion from the piston to the cross-head.

8. *Cross-head.* It is a link between the piston rod and connecting rod. Its function is to guide motion of the piston rod and to prevent it from bending.

9. *Connecting rod.* It is made of the forged steel, whose one end is connected to the cross head and the other to the crank. Its function is to convert reciprocating motion of the piston (or cross head) into rotary motion of the crank.

10. *Crankshaft.* It is the main shaft of the engine having a crank. The crank works on the lever principle and produces rotary motion of the shaft. The crankshaft is supported on main bearings of the engine.

11. *Eccentric.* It is generally made of cast iron, and is fitted to the crank shaft. Its function is to provide reciprocating motion to the slide valve.

12. *Eccentric rod and valve rod.* The eccentric rod is made of forged steel, whose one end is fixed to the eccentric and other to the valve rod. Its function is to convert rotary motion of the crankshaft into to and fro motion of the valve rod. The valve rod connects the eccentric rod and the D-slide valve. Its function is to provide simple harmonic motion to the D-slide valve.

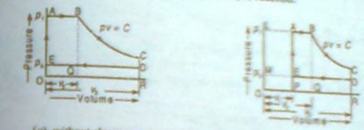
13. *Flywheel.* It is a heavy cast iron wheel, mounted on the crank shaft. Its function is to prevent the fluctuation of engine. It also prevents the jerks to the crankshaft.

14. *Governor.* It is a device to keep the engine speed, more or less, uniform at all load conditions. It is done either by controlling the quantity or pressure of the steam supplied to the engine.

6.23 Theoretical Indicator Diagram

The theoretical indicator diagram for a reciprocating steam engine without clearance (*i.e.* when there is no steam in the engine cylinder) and with clearance (*i.e.* when there is some steam in the engine cylinder) is shown in Fig. 6.2 (*a*) and (*b*) respectively.

The steam is admitted into the engine cylinder at point *A* at constant pressure (p_1) upto point *B*. Since at point *B*, the supply of steam is cut-off, therefore this point is known as *cut-off point*. The steam expands hyperbolically (*i.e.* according to $pv = C$) from point *B* to point *C*. At point *C*, the exhaust valve opens and the steam is released from the cylinder to the exhaust. Due to the exhaust of steam, the pressure falls to back pressure (p_b). The point *C* is known as *release point*. At point *D*, the piston returns back and the exhaust of steam takes place at constant pressure (p_b) till the exhaust port is closed and the inlet port is open at point *E*. The fresh steam is admitted at point *E* which increases the pressure of the steam till the original position (point *A*) is reached.



(*a*) without clearance (*b*) with clearance

Fig. 6.2

First of all, let us consider the theoretical indicator diagram without clearance as shown in Fig. 6.2 (*a*).

Theoretical workdone per cycle,

$$W = \text{Area of figure } ABCDE$$

$$= \text{Area } OABQ + \text{Area } QBCR - \text{Area } OEDR$$

$$= p_1 v_2 + p_1 v_2 \log_e \left(\frac{v_3}{v_2}\right) - p_b \cdot v_3 = p_1 v_2 (1 + \log_e r) - p_b \cdot v_3$$

and theoretical mean effective pressure,

$$p_m = \frac{\text{Workdone}}{\text{Displacement volume}} = \frac{p_1 \cdot v_2 (1 + \log_e r) - p_b \cdot v_3}{v_3}$$

$$= \frac{p_1}{r}(1 + \log_e r) - p_b$$

where

$$r = \text{Expansion ratio} = \frac{\text{Swept volume}}{\text{Volume at cut-off}} = \frac{v_3}{v_2}$$

Now let us consider the theoretical indicator diagram with clearance as shown in Fig. 6.2 (*b*).

Theoretical workdone per cycle,

$$W = \text{Area of figure } ABCDE$$

$$= \text{Area } LBQO + \text{Area } BCRQ - \text{Area } DEPR - \text{Area } OLAP$$

$$= p_1 \cdot v_2 + p_1 \cdot v_2 \log_e \left(\frac{v_3}{v_2}\right) - p_b (v_3 - v_1) - p_1 \cdot v_1$$

$$= p_1 \cdot v_2 (1 + \log_e r) - p_b (v_3 - v_1) - p_1 \cdot v_1$$

and theoretical mean effective pressure,

$$p_m = \frac{\text{Workdone}}{\text{Displacement volume}} = \frac{p_1 v_2(1+\log_e r) - p_b(v_3 - v_1) - p_1 v_1}{v_3 - v_1}$$

Notes : 1. The ratio of clearance volume to the swept volume is called *clearance ratio.*

2. The ratio of swept volume to the volume at cut-off is called *expansion ratio.*

3. The ratio of volume at cut-off to the swept volume is known as *cut - off ratio.* It is the reciprocal of expansion ratio.

6.24 Actual Indicator diagram

The comparison of actual indicator diagram (drawn with firm lines) and theoretical indicator diagram (drawn with dotted lines) is shown in Fig. 6.3. The following points, regarding actual indicator diagram, are important :

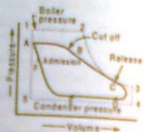


Fig. 6.3

1. The pressure of steam in the engine cylinder at the beginning of the stroke is less than the boiler pressure. This happens because of the fact that a certain pressure drop is necessary to produce a flow of steam from boiler to the engine cylinder.

2. During the forward stroke of the piston, there is always a slight fall in pressure (shown by line AB) due to wire drawing through the steam ports.

3. As the inlet port can not close instantaneously, the point of cut-off will not be sharp as 2, but rounded off as at B. The rounding of the cut-off point depends upon the type of valve and valve-mechanism employed.

4. The exhaust port opens before the end of the forward stroke (as shown by point C) due to wire drawing through exhaust ports. This causes the rounding off the toe of the diagram.

5. During the exhaust stroke, the pressure in the cylinder is higher than that of condenser pressure in case of condensing steam engines and higher than atmospheric pressure in case of non-condensing steam engines.

6. The exhaust valve closes at some point E, and the remaining steam in the cylinder is compressed along the curve EF before the end of the exhaust stroke. This reduces the wire drawing when the inlet valve opens at F and also reduces initial condensation. This also serves the purpose of cushioning, which gradually brings the piston to rest, and thus prevents the shock on the connecting rod bearings, which would otherwise be produced.

7. Due to wire drawing effects, the steam is admitted just before the end of exhaust stroke at F. The pressure produced by compression upto this point is raised to admission pressure by the time piston has reached at the end of exhaust stroke.

Notes : 1. The effect of wire drawing is to decrease the area of diagram. In other words, work done by the engine is reduced. This is, however, compensated by the fact that the wire drawing or throttling dries the steam slightly.

2. The effect of clearance, at the first sight, appears to increase the steam consumption from E to F. But the clearance increases the mean effective pressure and thus increases the work done. However, the net effect of the clearance is to decrease the efficiency. The increase in steam consumption may be reduced by making the point of compression earlier, and thus increasing the pressure obtained at F when the fresh steam is admitted to the cylinder. Earlier compression, however, decreases the area of diagram, *i.e.* work done is reduced.

6.25 Diagram Factor

The diagram factor (usually denoted by K) is the ratio of the area of actual indicator diagram to the area of theoretical indicator diagram. Mathematically, diagram factor,

$$K = \frac{\text{Area of actual indicator diagram}}{\text{Area of theoretical indicator diagram}}$$

We know that the area of the indicator diagram represents the work done per stroke. Therefore diagram factor may also be expressed mathematically,

$$K = \frac{\text{Actual work done per stroke}}{\text{Theoretical work done per stroke}}$$

We also know that work done /stroke

$$= \text{Mean effective pressure} \times \text{Swept volume}$$

$\therefore$ Actual work done / stroke

$$= \text{Actual m.e.p.} \times \text{Swept volume}$$

and theoretical work done /stroke

$$= \text{Theoretical m. e. p.} \times \text{Swept volume}$$

$$\therefore \quad K = \frac{\text{Actual mean effective pressure } (p_a)}{\text{Theoretical mean effective pressure } (p_m)}$$

The diagram factor may, therefore, be defined as the ratio of actual mean effective pressure to the theoretical mean effective pressure.

Notes : 1. The value of the diagram factor, to be used in any particular case, depends upon a number of factors such as initial condition of steam, initial pressure of steam, back pressure, speed of the engine, type of the engine, type of the valves, etc.

2. An average value of K lies between 0.65 and 0.9.

3. Actual mean effective pressure,

$$p_a = \text{Theoretical m.e.p.} \times \text{Diagram factor} = p_m \times K$$

6.26 Indicated Power

The actual power generated in the engine cylinder is called *indicated power* (briefly written as I.P.). Mathematically,

$$\text{I.P.} = \frac{p_a . L.A.N}{60} \text{ watts} \qquad \text{...(for single acting engine)}$$

$$= \frac{2 p_a . L.A.N}{60} \text{ watts} \qquad \text{...(For double acting engine)}$$

where p_a = Actual m.e.p. in N/m²,

L = Length of stroke is metres,

A = Area of piston in m², and

N = Speed of the engine in r.p.m.

Note : Piston speed = $L.N$ m/min, for single acting engine, and

= $2 L.N$ m/min, for double acting engine.

6.27 Brake Power

The net power available at the crank shaft is known as *brake power* (briefly written as B. P.). It is measured with the help of rope brake or prony brake dynamometer. Mathematically, for a rope brake dynamometer,

$$\text{B. P.} = \frac{(W - S) \times (D + d) N}{60} \text{ watts}$$

where
W = Load suspended in newtons,
S = Spring balance reading in newtons,
D = Diameter of the flywheel in metres,
d = Diameter of the rope in metres, and
N = Speed of the engine in r.p.m.

For a prony brake dynamometer,

$$\text{B.P.} = \frac{W.L \times 2\pi N}{60} \text{ watts}$$

where
W = Weight suspended in newtons, and
L = Horizontal distance between the weight and the centre of the pulley in metres.

Note : The difference between indicated power and brake power is called *frictional power* (*i.e.* power lost in overcoming friction). Mathematically, frictional power,

$$\text{F.P.} = \text{I.P.} - \text{B.P.}$$

6.28 Efficiencies of Steam Engine

The following efficiencies of a steam engine are important :

1. *Mechanical efficiency.* It is the ratio of brake power to the indicated power. Mathematically, mechanical efficiency,

$$\eta_m = \text{B. P.} / \text{I. P.}$$

2. *Indicated thermal efficiency.* It is the ratio of heat equivalent to indicated power per minute to energy supplied in steam per minute.

Let
m_s = Mass of steam used in kg /min,
h = Total heat of steam supplied at admission pressure in kJ / kg, and
h_f = Sensible heat of feed water at back pressure in kJ / kg, from steam tables.

$\therefore$ Energy supplied in steam per minute

$$= m_s (h - h_f) \text{ kJ / min}$$

and heat equivalent to I. P. per minute

$$= \text{I.P. (in kW)} \times 60 \text{ kJ /min} \qquad \ldots (\because 1 \text{ kW} = 1 \text{ kJ/s})$$

$\therefore$ Indicated thermal efficiency

$$= \frac{\text{I.P.} \times 60}{m_s (h - h_f)}$$

3. *Brake thermal efficiency.* It is the ratio of heat equivalent to brake power per minute to the energy supplied in steam per minute. Mathematically, brake thermal efficiency

$$= \frac{\text{B.P.} \times 60}{m_s (h - h_f)}$$

4. *Overall efficiency.* It is the ratio of the work obtained at the crankshaft in a given time to the energy supplied by fuel during the same time. If m_F is the mass of fuel burnt per minute and C is the calorific valve of the fuel in kJ / kg, then

$$\text{Overall efficiency} = \frac{\text{B.P.} \times 60}{m_F \times C}$$

5. *Relative efficiency.* It is the ratio of thermal efficiency to the Rankine efficiency. Mathematically,

$$\text{Relative efficiency} = \frac{\text{Thermal efficiency}}{\text{Rankine efficiency}}$$

6.29 Saturation Curve and Missing Quantity

When a p-v curve for the mass of dry saturated steam is plotted on the actual indicator diagram, a curve (such as MN) is obtained. This curve is known as *saturation curve* as shown in Fig. 6.4. With the help of the saturation curve, the dryness fraction of steam, at all points of the expansion curve BC, is obtained. Thus, at any point K,

Fig. 6.4

$$\text{Dryness fraction of steam} = \frac{JK}{JL} = \frac{\text{Volume of steam in cylinder at } K}{\text{Volume of steam at } K \text{, if dry}}$$

The volume of steam represented by the line KL is called the volume of missing quantity at point K. Mathematically,

Missing quantity at point K

= Volume of steam given by saturation curve (JL) – Actual volume of steam in the cylinder (JK)

= Total mass of steam in the cylinder during expansion stroke – Mass of steam in the cylinder assuming dry saturated at K

= Cylinder feed – Indicated mass of steam

The missing quantity is mainly due to the cylinder condensation and a small amount of steam leakage past the valves and piston. The cylinder condensation or missing quantity may be reduced by the following methods.

1. By the efficient steam jacketing of the cylinder walls.
2. By superheating the steam supplied to the engine cylinder.
3. By lagging in pipe from the boiler to the engine cylinder with a non-conducting material.
4. By compounding the expansion of steam in two cylinders, instead of one cylinder. Or, in other words, by keeping the expansion ratio small in each cylinder.
5. By increasing the speed of the engine.

6.30 Governing of Simple Steam Engines

The governing of simple steam engines is done by the following two methods :

1. *Throttle governing.* The throttle governing, of simple steam engines, is a method of controlling the engine output by varying pressure of the intake steam. The pressure of intake steam is varied by opening or closing the throttle valve under the control of a centrifugal governor. It may be noted that

(a) In throttle governing, cut-off point of the engine cylinder remains the same.

(b) If load on the engine is increased, then pressure of the admission steam is also increased to suit the increased load.

(c) The throttle governing of a simple steam engine results in the reduction of its thermal efficiency, and as such is somewhat wasteful with regard to the steam. The reason for the same is that at any load (below the full load), the full pressure of the steam is not used. Moreover, due to constant cut-off, a large quantity of steam is used in every stroke. This also tends to lower the thermal efficiency of the engine.

2. *Cut-off governing.* The cut-off governing, of a simple steam engine, is a method of controlling the engine output by varying volume of intake steam. This is done by varying the cut-off point by a slide valve under the control of a centrifugal governor. It may be noted that

(a) In a cut-off governing, pressure of the intake steam remains the same.

(b) If load on the engine is increased, then pressure of the admission steam is also increased to suit the increased load.

(c) This method is more economical and efficient. That is why these days cut-off governing is mostly used. But it requires a special valve gear.

6.31 Steam Consumption (Willian's Law)

The amount of steam used by an engine is measured by weighing the condensate collected from the condenser into which the engine exhausts.

When the steam consumption per hour is plotted against the indicated power (*I.P.*) during a test on a throttle governed engine, it will be a straight line. This shows that the steam consumption per hour is directly proportional to *I. P.* It is called as Willian's law and the straight line is called Willian's line as shown in Fig. 6.5.

Fig. 6.5

Willian's law holds good only for a throttle-governed engine, because the ratio of expansion remains constant. This condition is not fulfilled in a cut-off governed engine. The Willian's line follows the law :

$$W = mP + C$$

where W = Steam consumption per hour,

m = A constant representing the shape of the Willian's line,

P = Indicated power, and

C = Another constant, *i.e.* no load steam consumption per hour.

6.32 Compound Steam Engines

We have already discussed that a steam engine, in which the expansion of steam takes place in more than one cylinder, is known as a *compound steam engine.* The cylinder, which receives the high pressure steam, in known as *high pressure (H.P.) cylinder.* The steam after expanding in the high pressure cylinder, exhausts into a larger cylinder known as *low pressure (L.P.) cylinder.* In this cylinder, the last stage of expansion is performed. The L.P. cylinder generally exhausts into a condenser. That is why, the compound steam engines are generally condensing type. But they may be non-condensing also. If the expansion of steam takes place in three cylinders, the engine is called *triple expansion engine.* Similarly, if the expansion is carried out in four cylinders, it is known *quadruple expansion engine.*

In case of triple expansion engines, the first stage of expansion is performed in H.P. cylinder, intermediate expansion takes place in intermediate pressure (I.P.) cylinder, and the last expansion is

completed in L.P. cylinder. In quadruple expansion engine, the intermediate expansion is carried out in two I.P. cylinders.

Following are the advantages of compounding the expansion of steam in two or more cylinders:

1. There is a considerable economy in steam for high pressure operations.
2. The temperature range per cylinder is reduced, with corresponding reduction in the condensation.
3. The ratio of expansion is reduced, thus reducing the length of stroke.
4. The leakage past the valves and piston is reduced, because of the reduced pressure difference across these parts.
5. The steam can be reheated after expansion in one cylinder, and before entering the next.
6. The mechanical balance can be made more nearly perfect, and therefore high speeds are possible.
7. In case of a breakdown, the engine can be modified to continue working on reduced load.
8. More uniform turning moment is exerted on the crank shaft, by spacing the cranks at 90° in the case of a two cylinder engines or at 120° in triple expansion engines. Thus a lighter flywheel is required.
9. The forces in the working parts are reduced, as the forces are distributed over more parts.
10. The cost of the engine, for the same power and economy, is less than that of a simple steam engine.

6.33 Classification of Compound Steam Engines

The compound steam engines may be classified according to the arrangement of cranks, and the angles between them. Two-cylinder compound engines are generally classified as :

1. Tandem type compound engines,
2. Woolf type compound engines, and
3. Receiver type compound engines.

In *tandem type compound engine,* the two cylinders (H.P. and L.P.) have a common piston rod working on the same crank (*i.e.* cranks are at 0° to each other).

In *woolf type compound engine,* the two cylinders (H.P. and L.P.) have different piston rods attached to two different cranks set of 180° to each other. These cranks are cast in the same crank shaft.

In *receiver type compound engine,* the two cylinders (H.P. and L. P.) have different piston rods attached to two different cranks set at 90° to each other. These cranks are cast in the same crank shaft.

Note : The woolf type and receiver type compound engines are cross compound engines. In cross compounding, the cylinders are arranged side by side and each cylinder has separate piston, connecting rod and crank.

6.34 Steam Condensers

A steam condenser is a closed vessel into which the steam is exhausted, and condensed after doing work in an engine cylinder or turbine. A steam condenser has the following two objects :

1. The primary object is to maintain a low pressure (below atmospheric pressure) so as to obtain the maximum possible energy from steam and thus to secure a high efficiency.

2. The secondary object is to supply pure feed water to the hot well, from where it is pumped back to the boiler.

Note : The low pressure is accompanied by low temperature and thus all condensers maintain a vacuum under normal conditions. The condensed steam is called condensate. The temperature of condensate is higher on leaving the condenser than that of circulating water at inlet. It is thus obvious, that the condensate will have a considerable liquid heat.

6.35 Advantages of a Condenser in a Steam Power Plant

Following are the main advantages of incorporating a condenser in a steam power plant :

1. It increases expansion ratio of steam, and thus increases efficiency of the plant.
2. It reduces back pressure of the steam, and thus more work can be obtained.
3. It reduces temperature of the exhaust steam, and thus more work can be obtained.
4. The sense of condensate (*i.e.* condensed steam) as feed for boilers reduces the cost of power generation.
5. The temperature of condensate is higher than that of fresh water. Therefore amount of heat supplied per kg of steam is reduced.

6.36 Classification of Condensers

The steam condensers may be broadly classified into the following two types, depending upon the way in which the steam is condensed :

1. Jet condensers or mixing type condensers and
2. Surface condensers or non-mixing type condensers.

Following are the important points of comparison between jet and surface condensers :

S. No.	*Jet condensers*	*Surface condensers*
1.	Cooling water and steam are mixed up.	Cooling water and steam are not mixed up.
2.	Less suitable for high capacity plants.	More suitable for high capacity plants.
3.	Condensate is wasted.	Condensate is reused.
4.	It requires less quantity of circulating water.	It requires a large quantity of circulating water.
5.	The condensing plant is economical and simple.	The condensing plant is costly and complicated.
6.	Its maintenance cost is low.	Its maintenance cost is high.
7.	More power is required for air pump.	Less power is required for air pump.
8.	High power is required for water pumping.	Less power is required for water pumping.

6.37 Dalton's Law of Partial Pressures

It states " *The pressure of the mixture of air and steam is equal to the sum of the pressures, which each constituent would exert, if it occupied the same space by itself.*" Mathematically, pressure in the condenser containing mixture of air and steam,

$$p_c = p_a + p_s$$

where p_a = Partial pressure of air, and

p_s = Partial pressure of steam.

6.38 Measurement of Vacuum in a Condenser

The vacuum, in general, may be defined as the difference between the atmospheric pressure and the absolute pressure. In the study of condensers, the vacuum is generally converted to correspond with a standard atmospheric pressure, which is taken as the barometric pressure of 760

mm of mercury. Mathematically, vacuum gauge reading corrected to standard barometre, or in other words, corrected vacuum

$$= 760 - (\text{Barometric reading} - \text{Vacuum gauge reading})$$

6.39 Vacuum Efficiency

It is ratio of actual vacuum to ideal vaccum. Mathematically, vacuum efficiency,

$$\eta_v = \frac{\text{Actual vacuum}}{\text{Ideal vacuum}}$$

where Actual vacuum = Barometric pressure — Actual pressure

Ideal vacuum = Barometric pressure — Ideal pressure

6.40 Condenser Efficiency

The condenser efficiency may be defined as the ratio of temperature rise of cooling water to the vacuum temperature *minus* inlet cooling water temperature. Mathematically, condenser efficiency,

$$\eta_c = \frac{\text{Temperature rise of cooling water}}{\text{Vacuum temperature} - \text{Inlet cooling water temperature}}$$

OBJECTIVE TYPE QUESTIONS

1. A closed vessel made of steel and used for the generation of steam is called a
   (*a*) steam boiler (*b*) steam turbine (*c*) steam condenser (*d*) steam injector
2. A good steam boiler is one which produces maximum quantity of steam with the given fuel.
   (*a*) Agree (*b*) Disagree
3. The selection of type and size of a steam boiler depends upon
   (*a*) the power required and working pressure
   (*b*) the geographical position of the power house
   (*c*) the fuel and water available
   (*d*) all of the above
4. In a fire tube boiler, the water is contained inside the tubes which are surrounded by flames and hot gases from outside.
   (*a*) True (*b*) False
5. In water tube boilers, the water passes through the tubes which are surrounded by flames and hot gases.
   (*a*) Yes (*b*) No
6. Which of the following is a fire tube boiler ?
   (*a*) Lancashire boiler (*b*) Babcock and Wilcox boiler
   (*c*) Yarrow boiler (*d*) none of these
7. Fire tube boilers are limited to a maximum working pressure of
   (*a*) 0.17 MN/m² (*b*) 1.7 MN/m² (*c*) 17 MN/m² (*d*) 170 MN/m²
8. Which of the following is a water tube boiler ?
   (*a*) Lancashire boiler (*b*) Babcock and Wilcox boiler
   (*c*) Locomotive boiler (*d*) Cochran boiler

7

Steam Nozzles and Turbines

7.1 Introduction

A steam nozzle is a passage of varying cross-section, which converts heat energy of steam into kinetic energy. The main use of a steam nozzle is in steam turbines, which produces a jet of steam with a high velocity. The smallest section of the nozzle is called throat. It may be noted that the steam enters the nozzle with a high pressure and negligible velocity. But leaves the nozzle with a high velocity and small pressure. The pressure, at which the steam leaves the nozzle, is known as *back pressure*. Moreover, no heat is supplied or rejected by the steam during flow through a nozzle. Therefore it is considered as adiabatic flow, and the corresponding expansion is considered as an adiabatic expansion. The expansion of steam in a nozzle follows the Rankine cycle. The following are the three types of nozzles :

1. *Convergent nozzle.* When the cross-section of a nozzle decreases continuously from entrance to exit, it is called a convergent nozzle as shown in Fig. 7.1 (*a*).

(*a*) Convergent. (*b*) Divergent. (*c*) Convergent-divergent.

Fig. 7.1

2. *Divergent nozzle.* When the cross-section of a nozzle increases continously from entrance to exit, it is called a divergent nozzle as shown in Fig. 7.1 (*b*).

3. *Convergent-divergent nozzle.* When the cross-section of a nozzle first decreases from its entrance to throat, and then increases from its throat to exit, it is called a convergent – divergent nozzle as shown in Fig. 7.1 (*c*). This type of nozzle is widely used these days in various types of steam turbines.

7.2 Nozzle Efficiency

When the steam flows through a nozzle, some loss in its total heat takes place due to friction between the nozzle surface and the flowing steam. The effect of friction is to increase the dryness fraction of steam. This is due to the fact that the energy lost in friction is transferred into heat, which tends to dry or superheat the steam.

The *nozzle efficiency* or the *coefficient of nozzle* is defined as the ratio of useful heat drop to the isentropic heat drop. Mathematically, nozzle efficiency,

$$K = \frac{\text{Useful heat drop}}{\text{Isentropic heat drop}}$$

7.3 Velocity of Steam Flowing Through a Nozzle

Let V_1 = Velocity of steam entering the nozzle in m / s,

V_2 = Velocity of steam leaving the nozzle in m / s,

h_1 = Enthalpy or total heat of steam entering the nozzle in kJ / kg, and

We know that enthalpy or heat drop during expansion,

$$h_d = (h_1 - h_2) \text{ kJ / kg}$$

and

$$V_2 = \sqrt{2000\,h_d + (V_1)^2} \text{ m / s}$$

If V_1 is negligible as compared to V_2, then

$$V_2 = \sqrt{2000\,h_d} = 44.72\sqrt{h_d} \text{ m / s}$$

Note : In actual practice, there is always a certain amount of friction present between the steam and nozzle surfaces. This reduces the heat drop by 10 to 15% and thus the exit velocity of steam is also reduced correspondingly. Thus the above relation may be written as :

$$V_2 = 44.72\sqrt{K \times h_d} \text{ m / s}$$

where K = Nozzle efficiency

7.4 Condition for Maximum Discharge

A nozzle is, normally, designed for maximum discharge by designing a certain throat which produces this condition.

Let p_1 = Initial pressure of steam, and

p_2 = Pressure of steam at throat.

There is only one value of the ratio p_2 / p_1, which produces maximum discharge from the nozzle. It is given by

$$\frac{p_2}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}} \quad \text{...(i)}$$

The ratio p_2 / p_1 is known as *critical pressure ratio* and the pressure p_2 at the throat is known as *critical pressure*.

The maximum value of the discharge per second is given by

$$m_{max} = \sqrt{\frac{2n}{n-1} \times \frac{p_1}{v_1}\left(\frac{2}{n+1}\right)^{\frac{2}{n-1}}} \text{ kg / s} \quad \text{...(ii)}$$

From this expression we see that in a convergent - divergent nozzle, the discharge depends upon the area of nozzle at throat and the initial conditions of the steam (*i.e.* pressure p_1 and v_1). It is independent of the exit conditions of the steam. It is thus obvious, that the discharge remains constant after the throat (*i.e.* in the divergent portion of the nozzle).

Notes : 1. When the steam is initially dry saturated, then n = 1.135. Substituting this value of n in equation (*i*), we get critical pressure ratio,

$$p_2 / p_1 = 0.577$$

2. When the steam is initially super heated, then n = 1.3. Substituting this value of n in equation (*i*), we get critical pressure ratio,

$$p_2 / p_1 = 0.546$$

3. It has been found experimentally that when the steam is initially wet, then

$$p_2 / p_1 = 0.582$$

4. The critical pressure gives the velocity of steam at the throat equal to the velocity of sound.

5. The flow in the convergent portion of the nozzle is subsonic and in the divergent portion it is supersonic.

6. To increase the velocity of steam above sonic velocity (supersonic) by expanding steam below the critical pressure, the divergent portion for the nozzle is necessary.

7.5 Supersaturated Flow through Nozzle

When dry saturated steam is expanded adiabatically or isentropically, it becomes wet. We know that the expansion of steam in an ideal nozzle is isentropic, which is accompanied by condensation process. If the steam is initially superheated, the condensation should start after it has become dry saturated. This is possible when the steam has proceeded through some distance in the nozzle and in a short interval of time. But from practical point of view, the steam has a great velocity (sometimes sonic and even supersonic). Thus the phenomenon of condensation does not take place at the expected rate. As a result of this, equilibrium between the liquid and vapour phase is delayed and the steam continues to expand in a dry state. The steam in such a set of conditions, is said to be *supersaturated* or in *metastable state*. It is also called *supercooled steam*, as its temperature at any pressure is less than the saturation temperature corresponding to the pressure. The flow of supersaturated steam, through the nozzle is called *supersaturated flow* or *metastable flow*. It may be noted that

1. The difference of supersaturated temperature and saturation temperature is known as *degree of undercooling*.

2. The ratio of pressures corresponding to supersaturated temperature and saturation temperature is known as *degree of supersaturation*.

The following are the effects in a nozzle in which supersaturation occurs :

1. Since the density of supersaturated steam is about eight times that of ordinary saturated vapour at the corresponding pressure, therefore the mass of steam discharged increases.
2. The entropy and specific volume of the steam increases.
3. The exit velocity of the steam reduces.
4. The dryness fraction of the steam increases.

7.6 Steam Turbines

A steam turbine is a prime mover in which rotary motion is obtained by the gradual change of momentum of the steam. We have already discussed that in a reciprocating steam engines, the steam acts on the piston, as a load or weight, *i.e.* the action of steam is *static*.

In a steam turbine, the force exerted on the blades is due to the velocity of steam. This is due to the fact that the curved blades by changing the direction of steam receive a force or impulse. The action of steam in this case is said to be *dynamic*. Thus the dynamical pressure of steam rotates the vanes, buckets or blades directly. The turbine blades are curved in such a way that the steam directed upon them enters without shock, though there is always some loss of energy by the friction upon the surface of blades. In general, a steam turbine, essentially, consists of the following two parts :

1. The nozzle or fixed blades in which the heat energy of high pressure steam is converted into kinetic energy, so that the steam issues from the nozzle with a very high velocity.

2. The moving blades which change the direction of steam issuing from the nozzle, so that a force acts on the blades due to change of momentum and propel them.

Note : The steam turbines work on Rankine cycle whereas the steam engine work on modified Rankine cycle.

7.7 Advantages of Steam Turbines over Reciprocating Steam Engines

Following are the important advantages of steam turbines over reciprocating steam engines :

1. A steam turbine may develop higher speeds and a greater steam range is possible.
2. The efficiency of a steam turbine is higher.
3. The steam consumption is less.
4. Since all the moving parts are enclosed in a casing, the steam turbine is comparatively safe.
5. A steam turbine requires less space and lighter foundations, as there are little vibrations.
6. There is less frictional loss due to fewer sliding parts.
7. The applied torque is more uniform to the driven shaft.
8. A steam turbine requires less attention during running. Moreover, the repair costs are generally less.

7.8 Classification of Steam Turbines

The steam turbines, in general, are classified into the following two types :

1. Impulse turbines, and 2. Reaction turbines.

In an *impulse turbine*, the pressure of steam is reduced in the nozzle and remains constant while passing through the moving blades. The velocity of steam is increased in the nozzle and is reduced while passing through the moving blades. The simplest type of impulse turbine is De-Laval turbine. The other types are Curtis, Rateau, and Zoelly impulse turbines.

In a *reaction turbine*, the pressure is reduced in the fixed blades as well as in moving blades. The velocity of steam is increased in the fixed blades and is reduced while passing through the moving blades. The simplest type of a reaction turbine is Parson's turbine.

7.9 Velocity Triangles for Moving Blade of an Impulse Turbine

Consider a steam jet entering a curved blade at *C* after leaving the nozzle. The jet glides over the inside surface and leaves the blade at *D* as shown in Fig. 7.2. The velocity triangles at inlet and outlet tips of the moving blade are drawn as shown in Fig. 7.2, in which

V_b = Linear velocity of the moving blade (*AB*).

V = Absolute velocity of steam leaving the nozzle or entering the moving blade (*AC*).

V_r = Relative velocity of jet to the moving blade (*BC*). It is the vectorial difference between V and V_b.

V_f = Velocity of flow at entrance of the moving blade. It is the vertical component of V.

V_w = Velocity of whirl at entrance of the moving blade. It is the horizontal component of V.

θ = Angle which the relative velocity of jet to the moving blade (V_r) makes with the direction of motion of the blade.

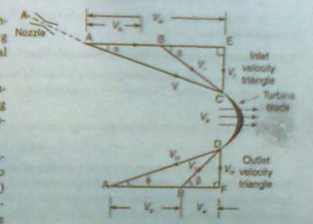


Fig. 7.2

α = Angle with the direction of motion of the blade at which the jet enters the blade.

$V_1, V_{r1}, V_{f1}, V_{w1}, \beta, \phi$ = Corresponding values at exit of the moving blade.

A little consideration will show, that as the steam jet enters and leaves the blades without any shock (or in other words tangentially), therefore shape of the blades will be such that V_r and V_{r1} will be along the tangents to the blades at inlet and outlet respectively.

For the sake of simplification, the inlet and outlet velocity triangles for the moving blade is combined as shown in Fig. 7.3. If m is the mass of steam flowing through the turbine in kg/s, then workdone by the steam on the blades

= Mass of steam × Change in velocity of whirl × Blade velocity

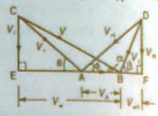


Fig. 7.3

$$= m\,(V_w \pm V_{w1})\,V_b \text{ N-m/s or J/s}$$
$$= m \times EF \times AB$$

$\therefore$ Power produced by the turbine

$$= m\,(V_w \pm V_{w1})\,V_b \text{ watts}$$

The *plus* sign is used when V_{w1} is in opposite direction with respect to the blade motion and *minus* sign is used when V_{w1} is in same direction with respect to the blade motion.

The axial thrust on the blades or on the wheel

$$= m\,(V_f - V_{f1}) = m \times (CE - DF) \text{ newton}$$

Notes : 1. When friction is neglected at the blade surfaces, then $V_{r1} = V_r$.

2. When there is a friction, then V_{r1} will be less than V_r and the ratio of V_{r1} to V_r is known as *blade velocity coefficient* or *coefficient of velocity* or *friction factor* (usually denoted by K).

3. The value of K varies from 0.75 to 0.85 depending upon the shape of the blades.

4. The energy lost due to friction in blades

$$= \frac{m\left[(v_r)^2 - (v_{r1})^2\right]}{2} \quad \text{N-m or J}$$

5. When there is no axial thrust on the blades, then $V_f = V_{f1}$.

6. When the steam leaves the blade at exit tip at 90° to the direction of blade motion (*i.e.* the turbine has axial discharge), then $V_{w1} = 0$.

7.10 Velocity Triangles for Moving Blades of a Reaction Turbine

The velocity triangles for the moving blades of a reaction turbine are drawn in the similar way as for an impulse turbine. The combined velocity triangle for a Parson's reaction turbine is shown in Fig. 7.4.

Since it is symmetrical about the centre line, therefore

$$V_f = V_{f1}\,;\; V = V_{r1}\,;\; V_r = V_1\,;\text{ and } EA = BF$$

The workdone by steam, the power developed and the axial thrust are obtained by using the same expressions as for impulse turbines. But in case of reaction turbine, the term *degree of reaction* is very important. It is defined as the ratio of enthalpy or heat drop in the moving blades to the total enthalpy or heat drop in fixed and moving blades. If m is the mass of steam flowing through the

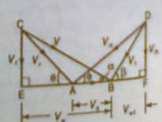


Fig. 7.4

turbine in kg / s, then heat drop through the fixed blades acting as nozzles

$$= \frac{m\,[V^2 - V_1^2]}{2} \quad \text{(in joules)}$$

and heat drop through the moving blades

$$= \frac{m\,[(V_{r1})^2 - (V_r)^2]}{2} \quad \text{(in joules)}$$

Note : The degree of reaction for Parson's turbine with symmetrical blades is 50 percent.

7.11 Efficiencies of Steam Turbines

The following efficiencies of impulse as well as reaction turbines are important :

1. *Diagram or blade efficiency.* It is the ratio of workdone on the blades to the energy supplied to the blades.

Let m = Mass of steam supplied in kg/s,

V = Absolute velocity of inlet steam in m/s,

V_b = Velocity of blade in m/s, and

$V_w \pm V_{w1}$ = Change in velocity of whirl in m/s.

We know that workdone on the blades per second

$$= m\,(V_w \pm V_{w1})\,V_b$$

and energy supplied to the blade = K.E of steam at inlet $= \dfrac{mV^2}{2}$

$\therefore$ Diagram or blade efficiency,

$$\eta_b = \frac{m\,(V_w \pm V_{w1})V_b}{m.V^2/2} = \frac{2(V_w \pm V_{w1})V_b}{V^2}$$

2. *Gross or stage efficiency.* It is the ratio of workdone on the blades per kg of steam to the total energy supplied or heat drop per stage per kg of steam. Mathematically, gross or stage efficiency,

$$\eta_s = \frac{(V_w \pm V_{w1})V_b}{h_d}$$

where h_d = Total energy supplied or heat drop per stage in joules per kg of steam.

3. *Nozzle efficiency.* It is the ratio of energy supplied to the blades per kg of steam to the total energy supplied per stage per kg of steam. Mathematically, nozzle efficiency,

$$\eta_n = V^2/2h_d$$

Note : We know that stage efficiency,

$$\eta_s = \frac{(V_w \pm V_{w1})V_b}{h_d} = \frac{2(V_w \pm V_{w1})V_b}{V^2} \times \frac{V^2}{2h_d}$$

$$= \text{Blade efficiency} \times \text{Nozzle efficiency} = \eta_b \times \eta_n$$

7.12 Condition for Maximum Efficiency

For maximum efficiency of an impulse turbine, the steam should leave the turbine blades at right angles to their motion. In other words, the velocity of whirl at the exit of moving blade is zero (i.e. $V_w = 0$). Therefore maximum efficiency of an impulse turbine,

$$\eta_{max} = \frac{2V_w \times V_b}{V^2}$$

The efficiency of De-Laval turbine is maximum, when

$$V_b = 0.5\,V_w = 0.5\,V\cos\alpha \qquad ...(\because V_w = V\cos\alpha)$$

where α = Nozzle angle.

$\therefore$ Maximum efficiency for De-Laval turbine,

$$\eta_{max} = \cos^2\alpha$$

In deriving the condition for maximum efficiency of reaction turbines, it is assumed that the fixed and moving blades are symmetrical and the degree of reaction is 50 percent. The efficiency of a reaction turbines is maximum when

$$V_b = V\cos\alpha$$

The maximum efficiency for a reaction turbine is given by

$$\eta_{max} = \frac{2\cos^2\alpha}{1+\cos^2\alpha}$$

7.13 Methods of Reducing Rotor Speeds

In power plants, high pressure and high temperature steam is used in order to increase their thermal efficiency. If the entire pressure drop (from the boiler pressure to condenser pressure) is carried out in one stage only, then the velocity of steam entering into the turbine will be extremely high. It will make the turbine rotor to run at a very high speed (even upto 30000 r.p.m.), which have a number of disadvantages.

In order to reduce the rotor speed, various methods are employed. All of these methods consist of a multiple system of rotors, in series, keyed to a common shaft and the steam pressure or the jet velocity is absorbed in stages as it flows over the rotor blades. This process is known as *compounding*. The following three methods are commonly employed for reducing the rotor speed :

1. *Velocity compounding*. In velocity compounding of an impulse turbine, the expansion of steam takes place in a nozzle or a set of nozzles from the boiler pressure to the condenser pressure. The impulse wheel carries two or three rows of moving blades.

The steam, after expanding through nozzles, enters the first ring of moving blades at a high velocity. A portion of this high velocity is absorbed by this blade ring and the remaining passed on to the next ring of fixed blades. The fixed blades change the direction of steam and direct it to the second ring of moving blades, without altering the velocity appreciably. After passing through this second ring of moving blades, a further portion of velocity is absorbed. The steam is now directed by the second ring of fixed blades to the third ring of moving blades and then enters into the condenser.

It may be noted that no pressure drop occurs either in the fixed or moving blades. All the pressure drop occurs in the nozzles. This turbine can run at about one-third of the speed of De-Laval turbine, for the same pressure drop and diameter of the wheel.

2. *Pressure compounding*. In pressure compounding of an impulse turbine, the rings of the moving blades, each having a ring of fixed nozzles, are keyed to the turbine shaft in series. The total pressure drop, of the steam, does not take place in the first nozzle ring, but is divided equally among all the nozzle rings.

The steam from the boiler is passed through the first nozzle ring, where only a small pressure drop occurs with an increase in velocity of steam. The steam is now directed on the first moving blade ring, where the pressure of steam does not alter, but the velocity decreases. This constitutes one stage. It may be noted that a stage consists of a fixed nozzle ring and a moving blade ring. The steam from the first moving blade ring enters the second nozzle ring, where its pressure is further reduced. A little consideration will show, that the pressure drop per stage in the nozzle rings is not the same. But the number of heat units, converted into velocity energy in each stage, is the same. The process is repeated in the remaining rings, until the condenser pressure is reached.

It may be noted that by arranging a small pressure drop per stage, the velocity of steam entering the moving blades, and hence the speed of rotor is reduced.

The Rateau and Zoelly turbines are the examples of pressure compounded turbines.

3. *Pressure-velocity compounding*. In a pressure-velocity compounding of an impulse turbine, both the previous two methods are utilised. The total pressure drop of the steam is divided into stages, and velocity obtained in each stage is also compounded. A little consideration will show, that a pressure velocity compounded impulse turbine allows a bigger pressure drop and hence less number of stages are required.

It may be noted that the diameter of the turbine is increased at each stage, to allow the increasing volume of steam at the lower pressures. A ring of nozzles is fixed at the commencement of each stage. A curtis turbine is an example of pressure-velocity compounded impulse turbine.

7.14 Governing of Steam Turbines

The function of a governor in a steam turbine is to maintain its speed constant irrespective of the load. It is done by controlling the supply of steam to the turbine. Though there are many methods of governing steam turbines, yet the following are important :

1. Throttle governing, 2. Nozzle control governing, and 3. By-pass governing.

In *throttle governing*, the steam admitted to the turbine is throttled so as to reduce the steam flow whenever there is a reduction of load, at the turbine. This is done by means of a balanced throttle valve which is operated by a servomotor controlled by a centrifugal governor.

In *nozzle control governing*, the nozzles of the turbine are grouped in two, three or more groups and each group of the nozzle is fed with the steam supply controlled by valves. The different types of arrangement of valves and groups of nozzles may be employed.

In *by-pass governing*, the steam enters the turbine chest through a main throttle valve which is controlled by a speed governor. For higher loads, a by-pass valve is opened. This valve is not opened until the lift of the throttle valve exceeds a certain amount. When the load decreases, the by-pass valve closes first. The by-pass valve is automatically regulated by a throttle valve (under the control of speed governor) which senses the effect of sudden decrease or increase of load.

7.15 Methods of Improving Steam Turbine Efficiency

The following methods are used to improve the efficiency of steam turbine :

1. Reheating of steam ; 2. Regenerative feed heating ; and 3. Binary vapour plants.

In *reheating of steam*, the steam is removed from the turbine when it becomes wet. It is then reheated at a constant pressure by the flue gases, until it is again in the superheated state. It is then returned to the next stage in the turbine.

The reheating of steam in a turbine has the following advantages :

1. It increases the work done through the turbine.

2. It increases the efficiency of the turbine.

3. It reduces the wear on the blades, because of low moisture contents in low pressure stages of the turbine.

In *regenerative feed heating*, the heat is transfered from the steam in the turbine to the liquid (condensate) flowing around the turbine, such that the temperature of steam and liquid being same at any section in the turbine.

The process of draining steam from the turbine, at certain points during its expansion and using this steam for heating the feed water (in feed water heaters) and then supplying it to the boiler is known as *bleeding*, and the corresponding steam is said to be bled. The effect of bleeding are :

1. It increases the thermodynamic efficiency of the turbine.
2. The boiler is supplied with a hot water.
3. A small amount of work is lost by the turbine, which decreases the power developed.

In a *binary vapour plant*, mercury and steam is used.

7.16 Reheat Factor

In steam turbines, the blade friction, shock, leakage etc. reduces the effective heat drop. This energy wasted in friction etc. reheats the steam and improves its quality as it emerges from the stage. The reheat factor is an important term used in multi-stage turbines which may be defined as the *ratio of the cumulative heat drop to the isentropic heat drop*.

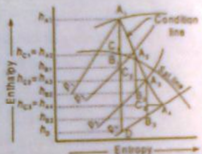


Fig. 7.5

Fig. 7.5 shows the expansion of steam in three stages, on a Mollier chart. $A_1 B_1$ is the isentropic heat drop for the first stage, out of which $A_1 C_1$ is the useful heat drop. The ratio $A_1 C_1$ to $A_1 B_1$ is the efficiency for the first stage. The condition of steam at exit from the first stage is represented by A_2 at pressure of B_1 (*i.e.* p_2) and total heat of C_1.

Similarly, for the second stage,

$$A_2 B_2 = \text{Isentropic heat drop, and}$$

$$A_2 C_2 = \text{Useful heat drop.}$$

$\therefore$ Efficiency for the second stage

$$= \frac{A_2 C_2}{A_2 B_2}$$

The condition of steam at exit from the second stage is represented by A_3 at pressure of B_2 (*i.e.* p_3) and total heat of C_2.

Now for the third stage,

$$A_3 B_3 = \text{Isentropic heat drop, and}$$

$$A_3 C_3 = \text{Useful heat drop.}$$

$\therefore$ Efficiency for the third stage

$$= A_3 C_3 / A_3 B_3$$

The condition of steam at exit from the third stage is represented by A_4 at pressure of B_3 (*i.e.* p_4) and total heat of C_3. The curve drawn through points A_1, A_2, A_3 and A_4 is known as *condition line*. The sum of the isentropic heat drop at each stage is called the *cumulative heat drop*. Thus for a three stage turbine.

$$\text{Cumulative heat drop} = A_1 B_1 + A_2 B_2 + A_3 B_3$$

$$\text{and isentropic heat drop} = A_1 D$$

$$\therefore \text{Reheat factor, R. F.} = \frac{\text{Cumulative heat drop}}{\text{Isentropic heat drop}} = \frac{A_1 B_1 + A_2 B_2 + A_3 B_3}{A_1 D} = \frac{\Sigma AB}{A_1 D}$$

The reheat factor depends on the following factors:

1. Stage efficiency of the turbine,
2. Initial pressure and temperature of steam,
3. Exit pressure of steam, and
4. Number of stages.

The reheat factor is more, if there are large number of stages. Its value varies from 1.02 to 1.06.

Due to reheat factor, the efficiency of the turbine as a whole is greater than the efficiency of individual stages. The efficiency of a complete turbine is known as *internal efficiency* or *efficiency ratio* of a turbine. It is defined as the ratio of total useful heat drop to the total isentropic heat drop. We know that

$$\text{Total useful heat drop} = A_1 C_1 + A_2 C_2 + A_3 C_3 \qquad \text{...(Refer Fig. 7.5)}$$

and total isentropic heat drop considering the complete turbine as a single stage

$$= A_1 D$$

$$\therefore \text{Internal efficiency} = \frac{A_1 C_1 + A_2 C_2 + A_3 C_3}{A_1 D}$$

Notes : 1. The ratio of the work delivered at the turbine shaft (in heat units) or the total useful heat drop to the heat supplied is known as *overall thermal efficiency* of the turbine.

2. The ratio of the total isentropic heat drop to the heat supplied is known as *Rankine efficiency*.

OBJECTIVE TYPE QUESTIONS

1. A steam nozzle converts
   (*a*) heat energy of steam into kinetic energy
   (*b*) kinetic energy into heat energy of steam
   (*c*) heat energy of steam into potential energy
   (*d*) potential energy into heat energy of steam
2. The expansion of steam in a nozzle follows
   (*a*) Carnot cycle (*b*) Rankine cycle (*c*) Joule cycle (*d*) Stirling cycle
3. The flow through a nozzle is regarded as
   (*a*) constant volume flow (*b*) constant pressure flow
   (*c*) isothermal flow (*d*) isentropic flow
4. During flow through a nozzle, no heat is supplied or rejected by the steam.
   (*a*) Agree (*b*) Disagree
5. The variation of steam pressure in the nozzle depends upon
   (*a*) velocity of steam (*b*) specific volume of steam
   (*c*) dryness fraction of steam (*d*) all of these

144. A binary vapour plant consists of

(*a*) steam turbine (*b*) steam condenser (*c*) mercury boiler (*d*) all of these

145. A steam turbine, in which a part of the steam after partial expansion, is used for process heating and the remaining steam is further expanded for power generation, is known as

(*a*) back pressure turbine (*b*) pass out turbine

(*c*) low pressure turbine (*d*) impulse turbine

ANSWERS

1. (*a*)	**2.** (*b*)	**3.** (*d*)	**4.** (*a*)	**5.** (*d*)	**6.** (*b*)
7. (*a*)	**8.** (*a*)	**9.** (*b*)	**10.** (*a*)	**11.** (*a*)	**12.** (*b*)
13. (*a*)	**14.** (*d*)	**15.** (*a*)	**16.** (*b*)	**17.** (*c*)	**18.** (*c*)
19. (*b*)	**20.** (*c*)	**21.** (*c*)	**22.** (*a*)	**23.** (*a*)	**24.** (*c*)
25. (*c*)	**26.** (*b*)	**27.** (*a*)	**28.** (*d*)	**29.** (*a*)	**30.** (*b*)
31. (*b*)	**32.** (*b*)	**33.** (*c*)	**34.** (*b*)	**35.** (*a*)	**36.** (*d*)
37. (*a*)	**38.** (*c*)	**39.** (*c*)	**40.** (*d*)	**41.** (*c*)	**42.** (*a*)
43. (*c*)	**44.** (*d*)	**45.** (*a*)	**46.** (*a*)	**47.** (*c*)	**48.** (*c*)
49. (*a*)	**50.** (*d*)	**51.** (*b*)	**52.** (*b*)	**53.** (*a*)	**54.** (*d*)
55. (*d*)	**56.** (*b*)	**57.** (*c*)	**58.** (*b*)	**59.** (*d*)	**60.** (*d*)
61. (*b*)	**62.** (*a*)	**63.** (*a*)	**64.** (*d*)	**65.** (*d*)	**66.** (*a*)
67. (*a*)	**68.** (*d*)	**69.** (*b*)	**70.** (*a*)	**71.** (*a*)	**72.** (*a*)
73. (*a*)	**74.** (*c*)	**75.** (*a*)	**76.** (*a*)	**77.** (*a*)	**78.** (*c*)
79. (*b*)	**80.** (*b*)	**81.** (*a*)	**82.** (*a*)	**83.** (*c*)	**84.** (*d*)
85. (*c*)	**86.** (*b*)	**87.** (*c*)	**88.** (*b*)	**89.** (*b*)	**90.** (*b*)
91. (*b*)	**92.** (*c*)	**93.** (*c*)	**94.** (*a*)	**95.** (*c*)	**96.** (*c*)
97. (*a*)	**98.** (*c*)	**99.** (*c*)	**100.** (*a*)	**101.** (*c*)	**102.** (*b*)
103. (*a*)	**104.** (*b*)	**105.** (*c*)	**106.** (*b*)	**107.** (*c*)	**108.** (*a*)
109. (*a*)	**110.** (*b*)	**111.** (*b*)	**112.** (*a*)	**113.** (*b*)	**114.** (*c*)
115. (*d*)	**116.** (*d*)	**117.** (*a*)	**118.** (*a*)	**119.** (*b*)	**120.** (*b*)
121. (*c*)	**122.** (*b*)	**123.** (*d*)	**124.** (*c*)	**125.** (*d*)	**126.** (*a*), (*b*)
127. (*D*), (*C*), (*B*), (*A*)		**128.** (*a*)	**129.** (*c*)	**130.** (*d*)	**131.** (*d*)
132. (*d*)	**133.** (*a*)	**134.** (*d*)	**135.** (*b*)	**136.** (*a*)	**137.** (*b*)
138. (*a*)	**139.** (*a*)	**140.** (*a*)	**141.** (*c*)	**142.** (*d*)	**143.** (*d*)
144. (*d*)	**145.** (*b*)				

8

I.C. Engines and Nuclear Power Plants

8.1 Introduction

The engines in which the combustion of fuel takes place inside the engine cylinder are called *internal combustion engines* (briefly written as I. C. engines). The working pressure and temperature inside the cylinder of an I.C. engine is very high. The efficiency of I. C. engines is about 35-40 percent.

8.2 Two Stroke and Four Stroke Cycle Engines

In a two stroke engine, the working cycle is completed in two strokes of the piston or one revolution of the crankshaft.

In a four stroke engine, the working cycle is completed in four strokes of the piston or two revolutions of the crankshaft.

8.3 Sequence of Operations in a Cycle

Strictly speaking, when an engine is working continuously, we may consider a cycle starting from any stroke. We know that when the engine returns back to the stroke where it started, we say that one cycle has completed. The following sequence of operation in a cycle is widely used.

1. *Suction stroke.* In this stroke, the fuel vapour in correct proportion, is supplied to the engine cylinder.

2. *Compression stroke.* In this stroke, the fuel vapour is compressed in the engine cylinder.

3. *Expansion or working stroke.* In this stroke, the fuel vapour is fired just before the compression is complete. It results in the sudden rise of pressure, due to expansion of the combustion products in the engine cylinder. This sudden rise of pressure pushes the piston with a great force and rotates the crankshaft. The crankshaft, in turn, drives the machine connected to it.

4. *Exhaust stroke.* In this stroke, the burnt gases (or combustion products) are exhausted from the engine cylinder, so as to make space available for the fresh fuel vapour.

8.4 Advantages and Disadvantages of Two Stroke over Four Stroke Cycle Engines

The following are the advantages and disadvantages of two stroke over four stroke cycle engines :

Advantages

1. A two stroke cycle engine gives twice the number of power strokes than the four stroke cycle engine at the same engine speed. Theoretically, a two stroke cycle engine should develop twice the power as that of a four stroke cycle engine.

2. For the same power developed, a two stroke cycle engine is lighter, less bulky and occupies less floor area.

3. A two stroke cycle engine has a lighter flywheel and gives higher mechanical efficiency than a four stroke cycle engine.

Disadvantages

1. The thermal efficiency of a two stroke cycle engine is less than that of a four stroke cycle engine, because a two stroke engine has less compression ratio than that of a four stroke cycle engine.

2. The overall efficiency of a two stroke cycle engine is also less than that of a four stroke cycle engine.

3. The consumption of lubricating oil is large in a two stroke cycle engine because of high operating temperature.

8.5 Valve Timing Diagram for a Four Stroke Cycle Petrol Engine

The petrol engines are also known as *spark ignition engines*. The valve timing diagram for a four stroke cycle petrol engine is shown in Fig. 8.1.

The following particulars are important for a four stroke cycle petrol engine regarding valve timing diagram :

(*a*) The inlet valve opens (IVO) at 10° – 20° before top dead centre (TDC) and closes 30° – 40° after bottom dead centre (BDC).

(*b*) The compression of charge starts at 30° – 40° after BDC and ends at 20° – 30° before TDC.

(*c*) The ignition (IGN) of charge takes place at 20° – 30° before TDC.

(*d*) The expansion starts at 20° – 30° before TDC and ends at 30° – 50° before BDC.

(*e*) The exhaust valve opens (EVO) at 30° – 50° before BDC and closes at 10° – 15° after TDC.

Fig. 8.1

Notes : (*i*) The inlet valve of a four stroke I. C. engine remains open for 230°.

(*ii*) The charge is compressed when both the valves (*i.e.* inlet valve and exhaust valve) are closed.

(*iii*) The charge is ignited with the help of a spark plug.

(*iv*) The pressure inside the engine cylinder is above the atmospheric pressure during the exhaust stroke.

8.6 Valve Timing Diagram for a Four Stroke Cycle Diesel Engine

The diesel engines are also known as *compression ignition engines*. The valve timing diagram for a four stroke cycle diesel engine is shown in Fig. 8.2.

The following particulars are important for a four stroke cycle diesel engine regarding valve timing diagram :

(*a*) The inlet valve opens at 10° – 20° before TDC and closes at 25° – 40° after BDC.

(*b*) The fuel valve opens at 10° – 15° before TDC and closes at 15° – 20° after TDC.

(*c*) The compression starts at 25° – 40° after BDC and ends at 10° – 15° before TDC.

(*d*) The expansion starts at 10° – 15° after TDC and ends at 30° – 50° before BDC.

(*e*) The exhaust valve opens at 30° – 50° before BDC and closes at 10° – 15° after TDC.

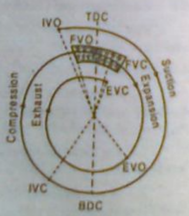


Fig. 8.2

Note : In diesel engines, the fuel is injected in the form of very fine spray into the engine cylinder, which gets ignited due to high temperature of the compressed air.

8.7 Comparison of Petrol and Diesel Engines

The following points are important for the comparison of petrol and diesel engines :

S.No.	*Petrol engines*	*Diesel engines*
1.	A petrol engine draws a mixture of petrol and air during suction stroke.	A diesel engine draws only air during suction stroke.
2.	The carburettor is employed to mix air and petrol in the required proportion and to supply it to the engine during suction stroke.	The injector or atomiser is employed to inject the fuel at the end of compression stroke.
3.	The pressure at the end of compression is about 10 bar.	The pressure at the end of compression is about 35 bar.
4.	The charge (*i.e.* petrol and air mixture) is ignited with the help of a spark plug.	The fuel is injected in the form of fine spray. The temperature of the compressed air (about 600° C at a pressure of about 35 bar) is sufficiently high to ignite the fuel.
5.	The combustion of fuel takes place approximately at constant volume. In other words, it works on Otto cycle.	The combustion of fuel takes place approximately at constant pressure. In other words, it works on Diesel cycle.
6.	A petrol engine has compression ratio approximately from 6 to 10.	A diesel engine has compression ratio approximately from 15 to 25.
7.	The starting is easy due to low compression ratio.	The starting is little difficult due to high compression ratio.
8.	As the compression ratio is low, the petrol engines are lighter and cheaper.	As the compression ratio is high, the diesel engines are heavier and costlier.
9.	The running cost of petrol engines is high because of the higher cost of petrol.	The running cost of diesel engines is low because of the lower cost of diesel.
10.	The maintenance cost is less.	The maintenance cost is more.
11.	The thermal efficiency is upto about 26%.	The thermal efficiency is upto about 40%.
12.	Overheating trouble is more due to low thermal efficiency.	Overheating trouble is less due to high thermal efficiency.
13.	These are high speed engines.	These are relatively low speed engines.
14.	The petrol engines are generally employed in light duty vehicles such as scooters, motorcycles, cars. These are also used in aeroplanes.	The diesel engines are generally employed in heavy duty vehicles such as buses, trucks, and earth moving machines etc.

8.8 Scavenging of I.C. Engines

The scavenging, in an internal combustion engine, is the process of removing the burnt gases from the combustion chamber of the engine cylinder. Though there are many types of scavenging, yet the following are important from the subject point of view :

1. *Crossflow scavenging.* In this method, the transfer port (or inlet port for the engine cylinder) and exhaust port are situated on the opposite sides of the engine cylinder (as in the case of two stroke cycle engines).

2. *Back flow or loop scavenging.* In this method, the inlet and outlet ports are situated on the same side of the engine cylinder.

3. *Uniflow scavenging.* In this method, the fresh charge, while entering from one side (or sometimes two sides) of the engine cylinder pushes out the gases through the exit valve situated on the top of the cylinder.

Note : The scavenging efficiency of a four stroke cycle diesel engine is between 95 and 100 percent.

8.9 Ignition System of Petrol Engines

The ignition in a petrol engine takes place by means of a spark plug at the end of the compression stroke. The voltage required to produce a spark across the gap between the sparking points of a plug is 6000 to 10000 volts. The following two ignition systems of petrol engines are important:

1. Coil ignition system (also known as battery ignition system); and
2. Magneto ignition system.

The *coil ignition system* has an induction coil, which consists of two coils known as primary and secondary coils wound on a soft iron core, as shown is Fig. 8.3. One end of the primary coil is

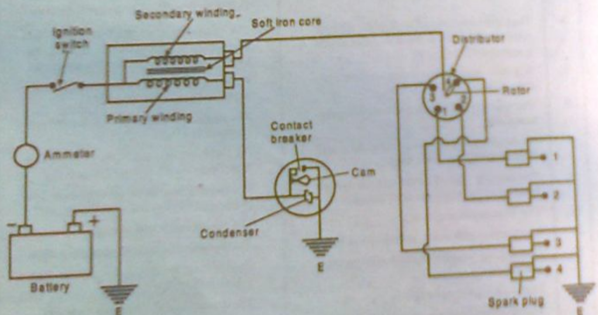


Fig. 8.3

connected to the ignition switch, ammeter and battery generally of 6 volts. The other end of the primary coil is connected to a condenser and a contact breaker. A condenser is connected across the contact breaker for the following two reasons :

(*a*) It prevents sparking across the gap between the points.

(*b*) It causes a more rapid break of the primary current, giving a higher voltage in the secondary circuit.

The secondary coil is connected to a distributor (in a multi-cylinder engine) with the central terminal of the sparking plugs. The outer terminals of the sparking plugs are earthed together and connected to the body of the engine.

The coil ignition system is employed in medium and heavy spark ignition engines such as in cars.

The *magneto ignition system* has the same principle of working as that of coil ignition system, except that no battery is required, as the magneto acts as its own generator. This type of ignition system is generally employed in small spark ignition engines such as scooters, motor cycles and small motor boat engines.

8.10 Supercharging of I.C. Engines

It is the process of increasing the mass (or in other words density) of the air fuel mixture (in spark ignition engines) or air (in compression ignition engines) induced into the engine cylinder. This is usually done with the help of a compressor or blower known as supercharger. It has been experimentally found that the supercharging increases the power developed by the engine. It is widely used in aircraft engines, as the mass of air sucked in the engine cylinder, decreases at very high altitudes. This happens, because atmospheric pressure decreases with the increase in altitude.

Following are the objects of supercharging the engines :

1. To reduce mass of the engine per brake power (as required in aircraft engines).
2. To maintain power of air craft engines at high altitudes where less oxygen is available for combustion.
3. To reduce space occupied by the engine (as required in marine engines).
4. To reduce consumption of lubricating oil (as required is all types of engines).
5. To increase the power output of an engine when greater power is required (as required in racing cars and other engines).

8.11 Lubrication of I. C. Engines

The lubrication of I. C. engines has the following advantages :

1. It reduces wear and tear of the moving parts.
2. It damps down the vibrations of the engine.
3. It dissipates the heat generated from the moving parts due to friction.
4. It cleans the moving parts.
5. It makes the piston gas-tight.

8.12 Governing of I.C. Engines

The process of providing any arrangement, which will keep the engine speed constant (according to the changing load conditions) is known as governing of I.C. engines. Though there are many methods for the governing of I.C. engines, yet the following are important :

1. *Hit and miss governing.* In this system of governing, whenever the engine starts running at higher speed (due to decreased load), some explosions are omitted or missed. This is done with the help of a centrifugal governor. This method of governing is widely used for I. C. engines of smaller capacity or gas engines.

2. *Qualitative governing.* In this system of governing, a control valve is fitted in the fuel delivery pipe, which controls the quantity of fuel to be mixed in the charge. The movement of control valve is regulated by the centrifugal governor through rack and pinion arrangement.

3. *Quantitative governing.* In this system of governing, the quality of charge (*i.e.* air-fuel ratio of the mixture) is kept constant. But the quantity of mixture supplied to the engine cylinder is varied by means of a throttle valve which is regulated by the centrifugal governor through rack and pinion arrangement.

4. *Combination system of governing.* In this system of governing, the qualitative and quantitative methods of governing are combined together.

8.13 Carburettor

The carburettor is a device for *atomising and **vaporising the fuel and mixing it with the air in the varying proportions to suit the changing operating conditions of the engine. The process of breaking up and mixing the fuel with the air is called *carburation*.

8.14 Spark Plug

A spark plug is a device used to produce spark for igniting the charge of petrol engines. It is always screwed into the cylinder head. It is, usually, designed to withstand a pressure upto 35 bar and operate under a current of 10 000 to 30 000 volts. The spark plug gap is kept from 0.3 mm to 0.7 mm.

8.15 Detonation in I.C. Engines

The loud pulsating noise heard within the engine cylinder of an I.C. engine is known as *detonation* (also called *knocking or pinking*). It is caused due to the propagation of a high speed pressure wave created by the auto-ignition of end portion of unburnt fuel. The blow of this pressure wave may be of sufficient strength to break the piston. Thus, the detonation is harmful to the engine and must be avoided. The following are certain factors which causes detonation :

1. The shape of the combustion chamber,
2. The relative position of the sparking plugs in case of petrol engines,
3. The chemical nature of the fuel,
4. The initial temperature and pressure of the fuel, and
5. The rate of combustion of that portion of the fuel which is the first to ignite. This portion of the fuel in heating up, compresses the remaining unburnt fuel, thus producing the conditions for auto-ignition to occur.

The detonation in petrol engines can be suppressed or reduced by the addition of a small amount of lead ethide or ethyl fluid to the fuel. This is called *doping*.

The following are the chief effects due to detonation:

1. A loud pulsating noise which may be accompanied by a vibration of the engine.
2. An increase in the heat lost to the surface of the combustion chamber.
3. An increase in carbon deposits.

8.16 Rating of S.I. Engine Fuels — Octane Number

The hydrocarbon fuels used in spark ignition (S.I.) engine have a tendency to cause engine knock when the engine operating conditions become severe. The knocking tendency of a fuel in S. I. engines is generally expressed by its octane number. The percentage, by volume, of iso-octane in a mixture of iso-octane and normal heptane, which exactly matches the knocking intensity of a given fuel, in a standard engine, under given standard operating conditions, is termed as the *octane number rating* of that fuel. Thus, if a mixture of 50 percent iso-octane and 50 percent normal heptane matches the knocking intensity of the fuel under test, then this fuel is assigned an octane number rating of 50. If a fuel matches in knocking intensity a mixture of 75 percent iso-octane and 25 percent normal heptane, then this fuel would be assigned an octane number rating of 75. This octane number rating is an expression which indicates the ability of a fuel *to resist knock in a spark ignition engine*.

* Atomisation is the mechanical breaking up of the liquid fuel into small particles so that every minute particle of the fuel is surrounded by air.

** Vaporisation is a change of state of fuel from a liquid to vapour.

Since iso-octane is a very good anti-knock fuel, therefore it is assigned a rating of 100 octane number. On the other hand, normal heptane has a very poor anti-knock qualities, therefore, it is given a rating of zero octane number. These two fuels, *i.e.*, iso-octane and normal heptane are known as primary reference fuels. It may be noted that higher the octane number rating of a fuel, the greater will be its resistance to knock and higher will be the compression ratio. Since the power output and specific fuel consumption are functions of compression ratio, therefore we may say that these are also functions of octane number rating. This fact indicates the extreme importance of the octane number rating in fuels for S. I. engines.

Note : The octane number of petrol, generally available, is 80 to 100.

8.17 Rating of C. I. Engine Fuels — Cetane Number

The knocking tendency is also found in compression ignition (C. I.) engines with an effect similar to that of S. I. engines, but it is due to a different phenomenon. The knock is C. I. engines is due to sudden ignition and abnormally rapid combustion of accumulated fuel in the combustion chamber. Such a situation occurs because of an ignition lag in the combustion of the fuel between the time of injection and the actual burning.

The property of ignition lag is generally measured in terms of cetane number. It is defined as the percentage, by volume, of cetane in a mixture of cetane and alpha-methyl-naphthalene that produces the same ignition lag as the fuel being tested, in the same engine and under the same operating conditions. For example, a fuel of cetane number 50 has the same ignition quality as a mixture of 50 percent cetane and 50 percent alpha-methyl-naphthalene.

The cetane which is a straight chain paraffin with good ignition quality is assigned a cetane number of 100 and alpha methyl-naphthalene which is a hydrocarbon with poor ignition quality, is assigned a zero cetane number.

Notes: 1. The knocking in C. I. engines may be controlled by decreasing ignition lag. The shorter the ignition lag, the lesser is the tendency to knock.

2. The cetane number of diesel oil, generally available, is 40 to 55.

8.18 Testing of I. C. Engines

The purpose of testing an internal combustion engine are :

(*a*) To determine the information which cannot be obtained by calculations.

(*b*) To conform the data used in design, the validity of which is doubtful.

(*c*) To satisfy the customer regarding the performance of the engine.

8.19 Thermodynamic Tests for I.C. Engines

An internal combustion is put to thermodynamic tests, so as to determine the following quantities :

1. *Indicated mean effective pressure.* The indicated mean effective pressure of an engine is obtained from the indicator diagram drawn with the help of an engine indicator. Mathematically, mean effective pressure (in bar)

$$= \frac{\text{Area of indicator card} \times \text{Scale of indicator spring}}{\text{Length of indicator card}}$$

It may be noted that the mean effective pressure calculated on the basis of theoretical indicator diagram, is known as *theoretical mean effective pressure*. If it is based on the actual indicator diagram then it is called *actual mean effective pressure*.

2. *Indicated power.* The indicated power (briefly written as I.P.) is the power actually developed by the engine cylinder. Mathematically,

$$\text{I.P.} = \frac{100\, K\, p_m\, L\, A\, n}{60}\ \text{kW}$$

where
K = Number of cylinders,
p_m = Actual mean effective pressure in bar,
L = Length of stroke in metres,
A = Area of the piston in m^2,
n = Number of working strokes per minute
= Speed of the engine for two stroke cycle engine
= Half the speed of the engine for four stroke cycle engine.

Note : The I.P. of a multi-cylinder is determined by *Morse test.*

3. *Brake power.* The brake power (briefly written as B.P.) is the power available at the crankshaft. The brake power of an I.C. engine is, usually, measured by means of a brake mechanism (prony brake or rope brake).

In case of prony brake, brake power of the engine,

$$\text{B.P.} = \frac{\text{Torque in N-m} \times \text{Angle turned in radians through 1 revolution}}{60}\ \text{(in watts)}$$

$$= \frac{T \times 2\pi N}{60} = \frac{Wl \times 2\pi N}{60}\ \text{watts}$$

where
W = Brake load in newtons,
l = Length of arm in metres, and
N = Speed of the engine in r.p.m.

In case of rope brake, brake power of the engine,

$$\text{B.P.} = \frac{(W - S)\pi D N}{60}\ \text{watts}$$

$$= \frac{(W - S)\pi (D + d) N}{60}\ \text{watts} \quad \text{...[Considering diameter } (d) \text{ of the rope]}$$

where
W = Dead load in newtons,
S = Spring balance reading in newtons,
D = Diameter of the brake drum in metres,
d = Diameter of the rope in metres, and
N = Speed of the engine in r.p.m.

Note : The brake power (B.P.) of an engine is always less than the indicated power (I.P.) of an engine, because some power is lost in overcoming the engine friction (known as frictional power). Mathematically,

Frictional power, F.P. = I.P. − B.P.

4. *Efficiency.* The efficiency of an engine is defined as the ratio of workdone to the energy supplied to an engine. The following efficiencies of an I.C. engine are important :

(*a*) *Mechanical efficiency.* It is the ratio of brake power (B.P.) to the indicated power (I.P.). Mathematically, mechanical efficiency,

$$\eta_m = \frac{\text{B.P}}{\text{I.P}}$$

Since B. P. is always less than I.P., therefore η_m is always less than unity (*i.e.* 100%).

(*b*) *Overall efficiency.* It is the ratio of the work obtained at the crankshaft in a given time to the energy supplied by the fuel during the same time. Mathematically, overall efficiency,

$$\eta_o = \frac{\text{B.P.} \times 3600}{m_f \times C}$$

where
B.P = Brake power in kW,
m_f = Mass of fuel consumed in kg per hour, and
C = Calorific valve of fuel in kJ / kg of fuel.

(*c*) *Indicated thermal efficiency.* It is the ratio of the heat equivalent to one kW hour to the heat in the fuel per I.P. hour. Mathematically, indicated thermal efficiency,

$$\eta_i = \frac{\text{Heat equivalent to one kW hour}}{\text{Heat in fuel per I.P. hour}} = \frac{\text{I.P.} \times 3600}{m_f \times C}$$

Note : The ratio $\frac{m_f}{\text{I.P.}}$ is known as specific fuel consumption per I.P. hour.

(*d*) *Brake thermal efficiency.* It is the ratio of the heat equivalent to one kW hour to the heat in the fuel per B.P. hour. Mathematically, brake thermal efficiency,

$$\eta_b = \frac{\text{Heat equivalent to one kW hour}}{\text{Heat in fuel per B.P. hour}} = \frac{\text{B.P.} \times 3600}{m_f \times C}$$

Note : The ratio $\frac{m_f}{\text{B.P.}}$ is known as specific fuel consumption per B. P. hour.

(*e*) *Air standard efficiency.* The general expression for the air standard efficiency is given as

$$\eta_{air} = 1 - \frac{1}{r^{\gamma - 1}} \quad \text{...(For petrol engines)}$$

$$= 1 - \frac{1}{r^{\gamma-1}}\left[\frac{\rho^{\gamma} - 1}{\gamma(\rho - 1)}\right] \quad \text{...(For diesel engines)}$$

where
r = Compression ratio,
γ = Ratio of specific heats, and
ρ = Cut-off ratio.

(*f*) *Relative efficiency.* It is also known as *efficiency ratio.* The relative efficiency of an I.C. engine is the ratio of the indicated thermal efficiency to the air standard efficiency.

(*g*) *Volumetric efficiency.* It is the ratio of the actual volume of charge admitted during the suction stroke at N.T.P. to the swept volume of the piston.

8.20 Nuclear Energy

The nuclear energy is the large amount of energy that can be released from a small mass of active material. The first nuclear power plant in India was located at Tarapur. The primary fuel used in nuclear power plants is Uranium (U_{235}). The isotopes of uranium are U_{234}, U_{235} and U_{238}, but U_{235} is mostly used. The secondary fuel used in nuclear power plants is Uranium (U_{233}) and Plutonium (P_{u239}). U_{233} is produced when thorium is irradiated by neutrons and P_{u239} is produced when U_{238} is irradiated by neutrons. The percentage composition of these naturally occurring isotopes in natural uranium are given as follows :

$$U_{234} = 0.006\% \; ; U_{235} = 0.712\% \; ; \text{and } U_{238} = 99.282\%.$$

The nuclear energy is generally represented by electron volt (ev) or million electron volt (Mev), such that

$$1 \text{ ev} = 1.602 \times 10^{-12} \text{ ergs} = 1.602 \times 10^{-19} \text{ watt second}$$

and

$$1 \text{ Mev} = 1.602 \times 10^{-6} \text{ ergs}$$

The energy released from uranium fission is about 200 million electron volt. It way be noted that

(*a*) Each fission of U_{235} produces on the average 2.46 fast neutrons as a product of reaction.

(*b*) A fission chain reaction in uranium can be developed by increasing the contents of U_{235} and by slowing down fast neutrons so that U_{235} fission continues by slow neutron.

8.21 Nuclear Reactors

The nuclear reactors are used for the following purposes :

1. To produce heat for thermoelectric power.
2. To produce fissiogable materials.
3. To propel ships, submarines and aircrafts.
4. For research testing and irradiation work.

The nuclear reactor has the following components :

(*a*) *Moderator*. A moderator is a material introduced into the fuel mass in order to slow down the speed of fast moving electrons. The slowing down of fast neutrons is desirable because slow moving electrons are more effective than fast neutrons in triggering fission. A moderator, apart from its high neutron slowing power and low non-productive neutron, should be

(*i*) Stable under nuclear radiation, (*ii*) Corrosion resistant,

(*iii*) good thermal conductor, and (*iv*) available in adequate.

The graphite and concrete are generally used as moderator.

(*b*) *Reflector*. A reflector is used to reflect neutrons back into the active core. Due to reflector, less fuel is needed to generate sufficient neutrons to sustain a chain reaction. The reflectivity of a reflector is defined as the fraction of neutrons entering the reflector which are returned to the core. It depends upon the geometry of the reflector, energy of neutrons and the properties of the reflector.

(*c*) *Control rods*. The control rods in the nuclear reactors are used to absorb excess neutrons.

OBJECTIVE TYPE QUESTIONS

1. The engines in which the combustion of fuel takes place inside the engine cylinder are called internal combustion engines.

(*a*) True (*b*) False

2. The working pressure and temperature inside the cylinder of an internal combustion engine is .... as compared to a steam engine.

(*a*) low (*b*) very low (*c*) high (*d*) very high

3. In a four stroke engine, the working cycle is completed in

(*a*) one revolution of the crankshaft (*b*) two revolutions of the crankshaft
(*c*) three revolutions of the crankshaft (*d*) four revolutions of the crankshaft

4. In a two stroke engine, the working cycle is completed in two revolutions of the crankshaft.

(*a*) Correct (*b*) Incorrect

5. A two stroke cycle engine gives .... the number of power strokes as compared to the four stroke cycle engine, at the same engine speed.

(*a*) half (*b*) same (*c*) double (*d*) four times

6. Theoretically, a four stroke cycle engine should develop .... power as that of a two stroke cycle engine.

(*a*) half (*b*) same (*c*) double (*d*) four times

7. A two stroke cycle engine occupies larger floor area than a four stroke cycle engine.

(*a*) Yes (*b*) No

8. A two stroke cycle engine gives .... mechanical efficiency than a four stroke cycle engine.

(*a*) higher (*b*) lower

9. The two stroke cycle engines have lighter flywheel.

(*a*) Agree (*b*) Disagree

10. Thermal efficiency of a two stroke cycle engine is .... a four stroke cycle engine.

(*a*) equal to (*b*) less than (*c*) greater than

11. The thermodynamic cycle on which the petrol engine works, is

(*a*) Otto cycle (*b*) Joule cycle (*c*) Rankine cycle (*d*) Stirling cycle

12. In a four stroke cycle engine, the sequence of operations is

(*a*) suction, compression, expansion and exhaust
(*b*) suction, expansion, compression and exhaust
(*c*) expansion, compression, suction and exhaust
(*d*) compression, expansion, suction and exhaust

13. In a four stroke cycle petrol engine, the pressure inside the engine cylinder during the suction stroke is .... the atmospheric pressure.

(*a*) equal to (*b*) below (*c*) above

14. The theoretically correct mixture of air and petrol is

(*a*) 10 : 1 (*b*) 15 : 1 (*c*) 20 : 1 (*d*) 25 : 1

15. In a four stroke cycle petrol engine, the inlet valve

(*a*) opens at top dead centre and closes at bottom dead centre
(*b*) opens at 20° before top dead centre and closes at 40° after bottom dead centre
(*c*) opens at 20° after top dead centre and closes at 20° before bottom dead centre
(*d*) may open or close anywhere

16. In a four stroke cycle petrol engine, the compression

(*a*) starts at 40° after bottom dead centre and ends at 30° before top dead centre
(*b*) starts at 40° before bottom dead centre and ends at 30° after bottom dead centre
(*c*) starts at bottom dead centre and ends at top dead centre
(*d*) may start and end anywhere

73. (c)	74. (c)	75. (d)	76. (d)	77. (b)	78. (a)
79. (d)	80. (c)	81. (d)	82. (d)	83. (d)	84. (a)
85. (c)	86. (b)	87. (a)	88. (a)	89. (b)	90. (a)
91. (c)	92. (a)	93. (c)	94. (b)	95. (a)	96. (a)
97. (d)	98. (d)	99. (d)	100. (d)	101. (b)	102. (b)
103. (c)	104. (a)	105. (b)	106. (a)	107. (a)	108. (d)
109. (d)	110. (b)	111. (d)	112. (d)	113. (b)	114. (a)
115. (d)	116. (d)	117. (a)	118. (c)	119. (c)	120. (a)
121. (a)	122. (c)	123. (a)	124. (b)	125. (c)	126. (b)
127. (d)	128. (d)	129. (c)	130. (b)	131. (a)	132. (c)
133. (a)	134. (b)	135. (b)	136. (c)	137. (a)	138. (a)
139. (a)	140. (d)	141. (b)	142. (a)	143. (c)	144. (c)
145. (a)	146. (a)	147. (b)	148. (a)	149. (d)	150. (d)
151. (d)	152. (d)	153. (d)	154. (a)	155. (b)	156. (c)
157. (a)	158. (b)	159. (a)	160. (b)	161. (b)	162. (d)
163. (a)	164. (b)	165. (b)	166. (a)	167. (b)	168. (a)
169. (d)	170. (a)	171. (c)	172. (b)	173. (b)	174. (c)
175. (a)	176. (a)	177. (c)	178. (c)	179. (b)	180. (b)
181. (a)	182. (b)	183. (b)	184. (d)	185. (c)	186. (d)
187. (c)	188. (d)	189. (c)	190. (a)	191. (c)	192. (c)
193. (b)	194. (a)	195. (c)	196. (a)	197. (b)	198. (a)
199. (b)	200. (d)	201. (b)	202. (a)	203. (b)	204. (a)
205. (c)	206. (d)	207. (c)	208. (b)	209. (a)	210. (a)
211. (a)	212. (c)	213. (a)	214. (d)	215. (a)	216. (d)
217. (b)	218. (a)	219. (d)	220. (d)	221. (d)	222. (c)
223. (d)	224. (b)	225. (a)	226. (d)	227. (a)	228. (b)
229. (b)	230. (a)	231. (a)	232. (d)	233. (d)	234. (a)
235. (a)	236. (c)	237. (a)	238. (a)	239. (c)	240. (c)

9

Compressors, Gas Dynamics and Gas Turbines

9.1 Introduction

An air compressor is a machine used to compress the air and to raise its pressure. The compressed air is used for many purposes such as for operating pneumatic drills, riveters, road drills, paint spraying, in starting and supercharging of internal combustion engines, in gas turbine plants, jet engines and air motors etc. It is also utilised in the operation of lifts, rams, pumps and a variety of other devices. In industry, compressed air is used for producing blast of air in blast furnaces and bessemer converters.

9.2 Important Terms used in Air Compressors

The following important terms are frequently used in air compressors :

1. *Inlet pressure.* It is the absolute pressure of air at the inlet of a compressor.
2. *Discharge pressure.* It is the absolute pressure of air at the outlet of a compressor.
3. *Compression ratio (or Pressure ratio).* It is the ratio of discharge pressure to the inlet pressure. Since the discharge pressure is always more than the inlet pressure, therefore the compression ratio is more than unity.
4. *Compressor capacity.* It is the volume of air delivered by the compressor, and is expressed in m^3/min or m^3/s.
5. *Free air delivery.* It is the actual volume delivered by a compressor when reduced to the normal temperature and pressure conditions. The capacity of a compressor is generally given in terms of free air delivery.
6. *Swept volume.* It is the volume of air sucked by the compressor during its suction stroke.
7. *Mean effective pressure.* It is the ratio of the workdone per cycle to the stroke volume of the compressor.

9.3 Workdone by a Single Stage Reciprocating Air Compressor without Clearance Volume

The p - v and T - s diagrams of a single acting, single stage reciprocating air compressor without clearance volume is shown in Fig. 9.1

Let p_1 = Initial pressure of air (before compression),

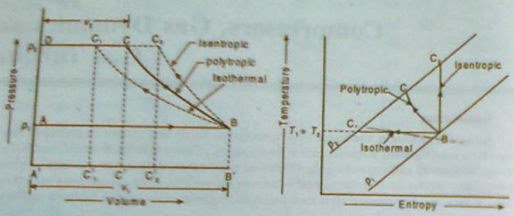
v_1 = Initial volume of air (before compression),

T_1 = Initial temperature of air (before compression),

p_2, v_2, T_2 = Corresponding valves for the final conditions (*i.e.* at the delivery point),

and r = Pressure ratio (*i.e.* p_2/p_1).

The air is sucked from the atmosphere during the suction stroke AB at pressure p_1. It is compressed at constant temperature ($T_1 = T_2$) during the compression stroke BC. The compression continues till the pressure (p_2) in the cylinder is sufficient to force open the delivery valve at C.



(a) p-v diagram. (b) T-s diagram.

Fig. 9.1

The compression of air may be isothermal, polytropic or isentropic (reversible adiabatic). The amount of workdone is compressing the air in all these three cases is as follows:

1. When compression of air is isothermal, then workdone by the compressor per cycle,

$$W = \text{Area of } p\text{-}v \text{ diagram } A\,B\,C_1\,D = 2.3\ p_1 v_1 \log r = 2.3\ m\,R\,T_1 \log r$$

2. When compression of air is polytropic (*i.e.* according to the law pv^n = constant), then workdone by the compressor per cycle,

$$W = \text{Area of } p\text{-}v \text{ diagram } A\,B\,C\,D = \frac{n}{n-1}(p_2 v_2 - p_1 v_1)$$

$$= \frac{n}{n-1} \times p_1 v_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right] = \frac{n}{n-1} \times mR\,(T_2 - T_1)$$

3. When compression of air is isentropic (*i.e.* according to the law pv^γ = constant), then workdone by the compressor per cycle,

$$W = \text{Area of } p\text{-}v \text{ diagram } ABC_2D = \frac{\gamma}{\gamma-1}(p_2 v_2 - p_1 v_1) = \frac{\gamma}{\gamma-1} \times p_1 v_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]$$

$$= \frac{\gamma}{\gamma-1} \times mR\,(T_2 - T_1) = mc_p(T_2 - T_1)$$

We see that the workdone per cycle during isentropic compression is equal to the heat required to raise the temperature of air from T_1 to T_2 at a constant pressure.

Note : The work done is compressing the air is minimum when compression is isothermal (*i.e.* when $n = 1$) and it is *maximum* when compression is isentropic (*i.e.* when $n = \gamma$) because isothermal line has less slope than isentropic line. It may be noted that in order to perform isothermal process, the compression should be very slow so that the temperature is maintained constant, which is not possible is actual practice. However, the isothermal compression may be approached, if

(a) the air or water cooling is done during the compression,

(b) the cold water is sprayed (injected) in the cylinder during the compression, and

(c) in multi-stage compressors, intercooling is done.

9.4 Workdone by Reciprocating Air Compressor with Clearance Volume

The p–v diagram of a single stage, single acting reciprocating air compressor with clearance volume (v_c) is shown in Fig. 9.2.

Though the compression and expansion of air may be isothermal, polytropic or isentropic, yet is assumed to be polytropic. We know that workdone by the compressor per cycle,

$$W = \text{Area } 1\text{–}2\text{–}3\text{–}4$$

$$= \frac{n}{n-1} \times p_1 (v_1 - v_4) \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{n}{n-1} \times m\,R\,T_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$$

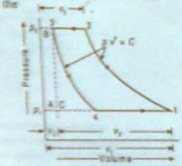


Fig. 9.2

where $(v_1 - v_4)$ and m is equal to the actual volume and mass of air sucked by the piston per cycle respectively. It may be noted that the clearance volume does not effect the workdone on the air and the power required for compressing the air.

9.5 Multi-stage Compression

Sometimes, the air is required at a high pressure. In such cases, either we employ a large pressure ratio (in a single cylinder) or compress the air in two or more cylinders which is known as *multi-stage compression*. Following are the main advantages of multi-stage compression over single stage compression :

1. The workdone per kg of air is reduced in multistage compression with intercooler as compared to single stage compression for the same delivery pressure.
2. It improves the volumetric efficiency for the given pressure ratio.
3. The sizes of the two cylinders (*i.e.* high pressure and low pressure) may be adjusted to suit the volume and pressure of air.
4. It reduces the leakage loss considerably.
5. It gives more uniform torque and hence a smaller size flywheel is required.
6. It provides effective lubrication because of lower temperature range.
7. It reduces the cost of compressor.

9.6 Two-stage Reciprocating Air Compressor with Intercooler

A two-stage reciprocating air compressor with intercooler is shown in Fig. 9.3. The following simplifying assumptions are made in case of a two-stage reciprocating air compressor with intercooler:

1. The effect of clearance is neglected.
2. There is no pressure drop in the intercooler.
3. The compression in both the cylinders (*i.e.* L.P. and H.P.) is polytropic (*i.e.* $pv^n = C$).
4. The suction and delivery of air takes place at constant pressure.

The efficiency of the intercooler plays an important role in the working of a two-stage reciprocating air compressor. Following two types of intercooling are important :

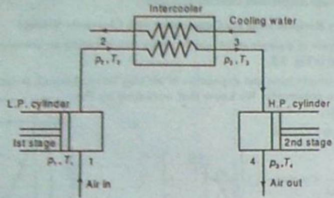
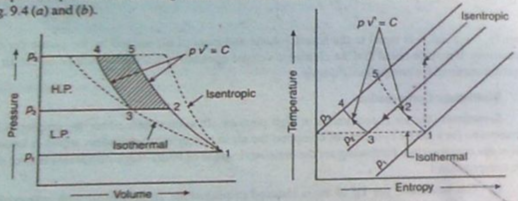


Fig. 9.3

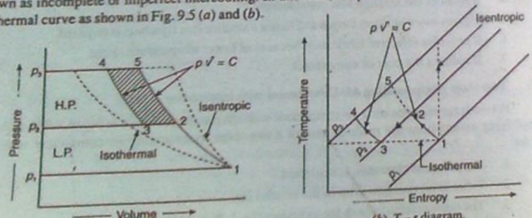
(a) *Complete or perfect intercooling.* When the temperature of the air leaving the intercooler (*i.e.* T_3) is equal to the original atmospheric air temperature (*i.e.* T_1), then the intercooling is known as complete or perfect intercooling. In this case, the point 3 lies on the isothermal curve as shown in Fig. 9.4 (a) and (b).



(a) $p-v$ diagram. (b) $T-s$ diagram.

Fig. 9.4

(b) *Incomplete or imperfect intercooling.* When the temperature of the air leaving the intercooler (*i.e.* T_3) is more than the original atmospheric air temperature (*i.e.* T_1), then the intercooling is known as incomplete or imperfect intercooling. In this case, the point 3 lies on the right-side of the isothermal curve as shown in Fig. 9.5 (a) and (b).



(a) $p-v$ diagram. (b) $T-s$ diagram.

Fig. 9.5

9.7 Workdone by a Two-stage Reciprocating Air Compressor with Intercooler

Consider a two-stage reciprocating air compressor with intercooler compressing air in its L.P. and H.P. cylinders.

Let p_1 = Pressure of air entering the L.P. cylinder,

v_1 = Volume of the L.P. cylinder,

p_2 = Pressure of air leaving the L.P. cylinder or entering the H.P. cylinder,

v_2 = Volume of the H.P. cylinder,

p_3 = Pressure of air leaving the H.P. cylinder, and

n = Polytropic index for both the cylinders.

Now we shall consider both the cases of incomplete intercooling as well as complete intercooling.

1. *When the intercooling is incomplete*

We know that workdone per cycle in L.P. cylinder,

$$W_1 = \frac{n}{n-1} \times p_1 v_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right] \qquad ...(i)$$

Similarly, workdone per cycle in H.P. cylinder,

$$W_2 = \frac{n}{n-1} \times p_2 v_2 \left[\left(\frac{p_3}{p_2}\right)^{\frac{n-1}{n}} - 1\right] \qquad ...(ii)$$

∴ Total workdone per cycle,

$$W = W_1 + W_2 = \frac{n}{n-1} \times p_1 v_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right] + \frac{n}{n-1} \times p_2 v_2 \left[\left(\frac{p_3}{p_2}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \frac{n}{n-1}\left[p_1 v_1 \left\{\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right\} + p_2 v_2 \left\{\left(\frac{p_3}{p_2}\right)^{\frac{n-1}{n}} - 1\right\}\right] \qquad ...(iii)$$

2. *When the intercooling is complete*

In case of complete intercooling, $p_1 v_1 = p_2 v_2$. Therefore substituting this valve in equation (*iii*),

$$W = \frac{n}{n-1} \times p_1 v_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} + \left(\frac{p_3}{p_2}\right)^{\frac{n-1}{n}} - 2\right] \qquad ...(iv)$$

$$= \frac{n}{n-1} \times mRT_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} + \left(\frac{p_3}{p_2}\right)^{\frac{n-1}{n}} - 2\right] \qquad ...(v)$$

From the above expressions, we see that the maximum work is saved in a two stage reciprocating air compressor with complete intercooling.

The work required to drive the compressor is minimum, when the pressure ratio in each stage is same, *i.e.*

$$\frac{p_2}{p_1} = \frac{p_3}{p_2} = \left[\frac{p_3}{p_1}\right]^{1/2} \qquad \text{...(vi)}$$

or

$$p_2 = \sqrt{p_1 \times p_3} \qquad \text{...(vii)}$$

Now substituting the value of $\frac{p_3}{p_2} = \frac{p_2}{p_1}$ in equation (*iv*), we have minimum work required for a two stage reciprocating air compressor,

$$W = 2 \times \frac{n}{n-1} \times p_1 v_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right] \qquad \text{...(viii)}$$

$$= 2 \times \text{Work required for each stage}$$

Again substituting $\frac{p_2}{p_1} = \left(\frac{p_3}{p_1}\right)^{1/2}$ in equation (*viii*),

$$W = 2 \times \frac{n}{n-1} \times p_1 v_1 \left[\left(\frac{p_3}{p_1}\right)^{\frac{n-1}{2n}} - 1\right]$$

Similarly, for a three stage compressor,

$$\frac{p_2}{p_1} = \frac{p_3}{p_2} = \frac{p_4}{p_3} = \left(\frac{p_4}{p_1}\right)^{1/3}$$

and minimum work required for a three stage compressor,

$$W = 3 \times \frac{n}{n-1} \times p_1 v_1 \left[\left(\frac{p_4}{p_1}\right)^{\frac{n-1}{3n}} - 1\right]$$

$$= 3 \times \frac{n}{n-1} \times mRT_1 \left[\left(\frac{p_4}{p_1}\right)^{\frac{n-1}{3n}} - 1\right]$$

$$= 3 \times \text{Work required for each stage}$$

9.8 Efficiencies of Reciprocating Air Compressor

The following efficiencies of reciprocating air compressor are important :

1. *Isothermal efficiency* (or *compressor efficiency*). It is the ratio of work (or power) required to compress the air isothermally to the actual work required to compress the air for the same pressure ratio.

2. *Overall isothermal efficiency*. It is the ratio of isothermal power to the shaft power or brake power of the motor or engine required to drive the compressor.

3. *Mechanical efficiency*. It is the ratio of the indicated power to the shaft power or brake power of the motor or engine required to drive the compressor.

4. *Isentropic efficiency*. It is the ratio of the isentropic power to the brake power required to drive the compressor.

5. *Volumetric efficiency*. It is the ratio of volume of free air delivery per stroke to the swept volume of the piston. The volumetric efficiency of a reciprocating air compressor with clearance volume is given by

$$\eta_v = 1 + K - K\left(\frac{p_2}{p_1}\right)^{1/n}$$

where

K = Clearance ratio = $\frac{\text{Clearance volume}}{\text{Swept volume of the piston}}$,

p_1 = Initial pressure of air (before compression),

p_2 = Final pressure of air (*i.e.* at the delivery point), and

n = Polytropic index.

9.9 Rotary Air Compressors

In a rotary air compressor, the air is entrapped between two sets of engaging surface and the pressure of air is increased by squeezing action or back flow of the air. It is driven either by an electric motor or an engine. The maximum delivery pressure is 10 bar only and the maximum free air discharge is as high as 3000 m³ / min. The speed of rotary air compressor is high as compared to reciprocating air compressor.

Following are the four types of rotary compressors :

1. Roots blower compressor, 2. Vane blower compressor, 3. Centrifugal blower compressor, and 4. Axial flow compressor.

The first two types are known as *positive displacement compressors* whereas the last two types are non-positive or *negative displacement compressors*.

Let us now discuss the above mentioned types of rotary compressors, in brief, as follows :

1. *Roots blower compressor*. A roots blower compressor, its simplest form, consists of two rotors with lobes rotating in an air tight casing which has inlet and outlet ports. Its action resembles with that of a gear pump. There are many design of wheels, but they generally have two or three lobes (and sometimes even more). In all cases, their action remains the same as shown in Fig. 9.6 (*a*) and (*b*). The lobes are so designed that they provide an air tight joint at the point of their contact.

The efficiency of roots blower (also known as roots efficiency) is given by

$$\eta = \frac{\gamma}{\gamma - 1} \times \frac{\left[r^{\frac{\gamma-1}{\gamma}} - 1\right]}{r - 1}$$

where r is the pressure ratio (*i.e.* p_2/p_1). We see that the efficiency of roots blower decreases with the increase in pressure ratio.

Note : The air is delivered four times in one revolution in case of a two lobbed rotor. Similarly, the air is delivered six times in one revolution in case of a three-lobbed rotor.

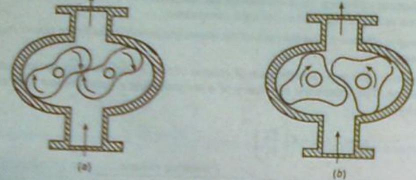


Fig. 9.6

2. *Vane blower compressor.* A vane blower, in its simplest form, consists of a disc rotating eccentrically in an air tight casing with inlet and outlet ports. The disc has a number of slots (generally 4 to 8) containing vanes. When the rotor rotates the disc, the vanes are pressed against the casing, due to centrifugal force, and form air tight pockets.

The efficiency of the vane blower (also known as vane blower efficiency) is given by

$$\eta = \frac{W_2}{W_1 + W_2}$$

where W_1 = Workdone due to compression, and

W_2 = Workdone due to back flow.

3. *Centrifugal compressor.* A centrifugal blower compressor, in its simplest form, consists of a rotor (or impeller) to which a number of curved vanes are fitted symmetrically. The rotor rotates in an air tight volute casing with inlet and outlet points. The casing for the compressor is so designed that the kinetic energy of air is converted into pressure energy before it leaves the casing, as shown in Fig. 9.7.

The curved vanes as well as the diffuser are so designed that the air enters and leaves their tips tangentially, *i.e.* without shock.

Fig. 9.7

4. *Axial flow compressors.* An axial flow compressor, in its simplest form, consists of a number of rotating blade rows fixed to a rotating drum. The drum rotates inside and air tight casing to which are fixed stator blade rows, as shown in Fig. 9.8. The blades are made of aerofoil section to reduce the loss caused by turbulence and boundary separation. As the drum rotates, the air flows through the alternately arranged stator and rotor. The flow of air is parallel to the axis of compressor.

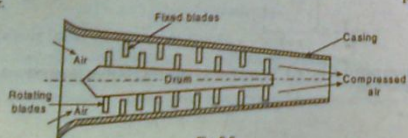


Fig. 9.8

In an axial flow compressor, the ratio of pressure in the rotor blades to the pressure rise in the compressor in one stage is known as *degree of reaction*.

9.10 Gas Turbines

In a gas turbine, first of all, the air is obtained from the atmosphere and compressed in an air compressor. The compressed air is then passed into the combustion chamber, where it is heated considerably. The hot air is then made to flow over the moving blades of the gas turbine, which imparts rotational motion to the runner. During this process, the air gets expanded and finally it is exhaused into the atmosphere. A major part of the power developed by the turbine is consumed for driving the compressor. The remaining power is utilised for doing some external work.

9.11 Comparison of Gas Turbines and Steam Turbines

Following are the points of comparison between gas turbines and steam turbines :

S.No.	*Gas Turbines*	*Steam Turbines*
1.	The important components are compressor and combustion chamber.	The important components are steam boiler and accessories.
2.	The mass of gas turbines ,per kW developed is less.	The mass of steam turbines per kW developed is less.
3.	It requires less space for installation.	It requires more space for installation.
4.	The installation and running cost is less.	The installation and running cost is more.
5.	The starting of gas turbine is very easy and quick.	The starting of steam turbine is difficult and takes long time.
6.	Its control with the changing load conditions, is easy.	Its control, with the changing load conditions, is difficult.
7.	A gas turbine does not depend on water supply.	A steam turbine depends on water supply.
8.	Its efficiency is less.	Its efficiency is higher.

9.12 Comparison of Gas Turbines and I.C. Engines

Following are the points of comparison between gas turbines and I.C. engines :

S.No.	*Gas Turbines*	*I.C. Engines*
1.	The mass of gas turbine per kW developed is less.	The mass of an I.C. engine per kW developed is more.
2.	The installation and running cost is less.	The installation and running cost is more.
3.	Its efficiency is higher.	Its efficiency is less.
4.	The balancing of a gas turbine is perfect.	The balancing of an I.C. engine is not perfect.
5.	The torque produced is uniform. Thus no fly-wheel is required.	The torque produced is not uniform. Thus flywheel is necessary.
6.	The lubrication and ignition systems are simple.	The lubrication and ignition system are difficult.
7.	It can be driven at a very high speed.	It can not be driven at a very high speed.

S.No.	Gas Turbines	I.C. Engines
8.	The pressures used are very low (about 5 bar).	The pressures used are high (above 60 bar).
9.	The exhaust of a gas turbine is free from smoke and less polluting.	The exhaust of an I.C. engine is more polluting.
10.	They are very suitable for air crafts.	They are less suitable for aircrafts.
11.	The starting of a gas turbine is not simple.	The starting of an I.C. engine is simple.

9.13 Classification of Gas Turbines

The gas turbines may be classified as follows :

1. *According to the path of the working substance*

(a) Closed cycle gas turbines, (b) Open cycle gas turbines, and

(c) Semi-closed gas turbines.

2. *According to the process of heat absorption*

(a) Constant pressure gas turbines, and (b) Constant volume gas turbines.

A closed cycle gas turbine, in its simplest form, consists of a compressor, heating chamber, gas turbine which drives the generator and compressor and a cooling chamber as shown in Fig. 9.9. It works on Joule's or Brayton's cycle. The air is heated in a heating chamber at constant pressure and expanded isentropically in the turbine. Similarly, the air is cooled in the cooling chamber at constant pressure and compressed isentropically in the compressor.

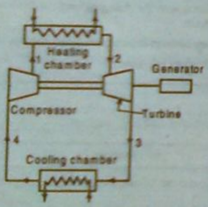


Fig. 9.9

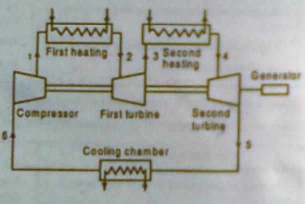


Fig. 9.10

The output of a gas turbine can be considerably improved by expanding the hot air in two stages with a reheater between the two, as shown in Fig. 9.10. The reheating in a gas turbine decreases the compressor work and increases the thermal efficiency of the turbines. For maximum work, the reheating should be done to an intermediate pressure of

$$p_3 = p_4 = \sqrt{p_2 \times p_5} = \sqrt{p_1 \times p_6} \qquad \ldots(\because p_1 = p_2 \text{ and } p_5 = p_6)$$

p_1 = Maximum pressure, and p_6 = Minimum pressure.

9.14 Open Cycle Gas Turbine

An open cycle gas turbine, in its simplest form, consists of a compressor, combustion chamber and a gas turbine which drives the generator and compressor, as shown in Fig. 9.11

Since the combustion of fuel takes place continuously, therefore, this turbine is also called a continuous combustion gas turbine. This turbine also works on Joule's cycle.

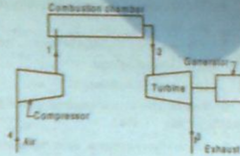


Fig. 9.11

9.15 Applications of Gas Turbines

The gas turbines are mainly used where the high power and speed are the primary considerations. The applications of gas turbines are as follows :

1. It is widely used in jet propulsion unit for air craft.
2. It can be used in ships as the propulsion unit.
3. It is used in the electric generating stations and in locomotives.
4. It is used in the process of supercharging.

9.16 Jet Propulsion

The propulsion unit which obtains the *oxygen for combustion purposes, from the surrounding atmosphere, is known as *jet propulsion*. It is used for the propulsion of high speed air craft, capable of operating at high speed. It may also be used in different types of missiles.

The propulsive efficiency is defined as the ratio of thrust power to the propulsive power.

Let m_a = Mass of flowing air in kg/s,

v_1 = Relative velocity of jet to aircraft in m/s, and

v_2 = Velocity of aircraft in m/s.

We know that thrust power

$$= m_a (v_1 - v_2) v_2$$

and propulsive power

$$= \frac{m_a (v_1^2 - v_2^2)}{2}$$

$$\therefore \text{ Propulsive efficiency} = \frac{\text{Thrust power}}{\text{Propulsive power}} = \frac{m_a (v_1 - v_2) v_2}{m_a (v_1^2 - v_2^2)/2} = \frac{2 v_2}{v_1 + v_2}$$

OBJECTIVE TYPE QUESTIONS

1. A machine used to raise the pressure of air is called
   (a) gas turbine (b) I.C. engine (c) compressor (d) air motor
2. A compressor must be driven by some prime mover.
   (a) Agree (b) Disagree
3. The compressed air may be used
   (a) in gas turbine plants (b) for operating pneumatic drills
   (c) in starting and supercharging of I.C. engines
   (d) all of the above

*When the aircraft uses its own oxygen for combustion, it is then known as *rocket propulsion*.

10

Heat Transfer, Refrigeration and Air Conditioning

10.1 Introduction

According to Second Law of Thermodynamics, heat transfer or heat flow takes place from a body at a higher temperature to a body at a lower temperature. Following are the three methods of heat transfer from one body to another :

1. *Conduction.* It is a process of heat transfer from one particle of the body to another in the direction of fall of temperature. The particles themselves remain in fixed position relative to each other. The heat transfer in a metal rod is by conduction.

2. *Convection.* It is a process of heat transfer from one particle of the body to another by convection current. In this case, the particles of the body move relative to each other. The heat transfer, in case of liquids and gases, takes place according to convection.

3. *Radiation.* It is a process of heat transfer from a hot body to a cold body, in a straight line, without affecting the intervening medium. The heat of sun reaches to us according to radiation.

10.2 Newton's Law of Cooling

The heat transfer from a hot body to a cold body is directly proportional to the surface area and difference of temperatures between the two bodies. This statement is called Newton's law of cooling.

10.3 Fourier's Law of Heat Conduction

It is an important law in heat conduction, which is represented by the equation,

$$Q \propto A \times \frac{dT}{dx} \quad \text{or} \quad Q = k\,A \times \frac{dT}{dx} \qquad ...(i)$$

where Q = Amount of heat flow through the body in a unit time,

A = Surface area of heat flow, taken at right angles to the direction of flow,

dT = Temperature difference on the two faces of the body,

dx = Thickness of the body through which the heat flows, taken along the direction of heat flow, and

k = Constant of proportionality known as thermal conductivity of the body

From above, we see that the amount of heat flow through a body by conduction is

(*a*) directly proportional to the surface area of the body,

(*b*) directly proportional to the temperature difference on the two faces of the body,

(*c*) inversely proportional to the thickness of the body, and

(*d*) dependent upon the material of the body.

10.4 Thermal Conductivity

We know that amount of heat flow through a body in a unit time,

$$Q = k\,A \times \frac{dT}{dx} = \frac{k\,A \times (T_1 - T_2)}{dx}$$

where T_1 = Higher temperature, and T_2 = Lower temperature

If t is the time through which the heat flows into a solid slab of thickness x, then total amount of heat flow through a body,

$$Q = \frac{k\,A \times (T_1 - T_2)\,t}{x} \qquad ...(ii)$$

In this equation, if we substitute $A = 1\,\text{m}^2$; $T_1 - T_2 = 1\,\text{K}$; $t = 1\,\text{s}$ and $x = 1\,\text{m}$, then $Q = k$.

Thus thermal conductivity of a material is numerically equal to the quantity of heat (in joules) which flows in one second through a slab of the material of area $1\,\text{m}^2$ and thickness 1 m when its faces differ in temperature by 1K. It may also be defined as the quantity of heat in joules that flows in one second through one metre cube of a material when opposite faces are maintained at a temperature difference of 1K. This may also be stated as the heat conducted in unit time across unit area through unit thickness when a temperature difference of unity is maintained between opposite faces.

The unit of thermal conductivity in S.I. units is J / m / K / s or W / mK

The rate of heat flow may also be written as

$$Q = \frac{T_1 - T_2}{x / kA}$$

The term x / kA is known as *thermal resistance* and $(T_1 - T_2)/x$ is called *temperature gradient*.

10.5 Heat Transfer by Conduction through a Composite Wall

Consider a composite wall consisting of two different materials through which the heat is being transferred by conduction, as shown in Fig. 10.1.

Let x_1 = Thickness of first material,

k_1 = Thermal conductivity of first material,

x_2 and k_2 = Corresponding values for the second material,

T_1 and T_3 = Temperatures of the two outer surfaces,

T_2 = Temperature at junction point, and

A = Surface area of the wall.

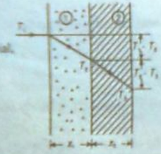


Fig. 10.1

Under steady conditions, the rate of heat flow is given by

$$Q = \frac{T_1 - T_3}{\dfrac{x_1}{k_1 A} + \dfrac{x_2}{k_2 A}} = \frac{T_1 - T_3}{\Sigma \dfrac{x}{k A}}$$

10.6 Radial Heat Transfer by Conduction Through a Thick Cylinder

The heat transfer through boiler tubes or refrigerator pipings are the examples of conduction of heat transferred radially through the walls of hollow thick cylindrical pipes.

Consider a thick pipe of length l carrying steam or hot liquid at a higher temperature as shown in Fig. 10.2

Let T_1 = Inside (higher) temperature of liquid,

T_2 = Outside (lower) temperature of the surroundings,

r_1 = Inside diameter of the pipe, and

r_2 = Outside diameter of the pipe.

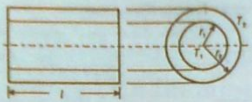


Fig. 10.2

The heat transfer by conduction through a thick cylinder (Q) is given by

$$Q = \frac{2\pi lk(T_1 - T_2)}{2.3\log(r_2/r_1)}$$

Note : In case of a composite cylinder, heat transfer,

$$Q = \frac{2\pi l(T_1 - T_2)}{\Sigma \frac{2.3}{k}\log\left(\frac{r_2}{r_1}\right)}$$

10.7 Heat Transfer by Conduction through a Thick Sphere

Consider a hollow thick spherical shell containing liquid at a higher temperature as shown in Fig. 10.3.

Let, T_1 = Inside (higher) temperature of the liquid,

T_2 = Outside (lower) temperature of the surroundings,

r_1 = Inside diameter of the sphere, and

r_2 = Outside diameter of the sphere.

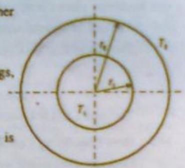


Fig. 10.3

The heat transfer by conduction through a thick sphere (Q) is given by

$$Q = \frac{4\pi k\, r_1 r_2 (T_1 - T_2)}{r_2 - r_1}$$

Note : In case of a composite sphere, heat transfer,

$$Q = \frac{4\pi(T_1 - T_2)}{\Sigma \frac{r_2 - r_1}{k r_1 r_2}}$$

10.8 Overall Coefficient of Heat Transfer

In actual practice, the heat from a hot body is transferred to the cold body by the combined effect of conduction and convection. Consider a wall through which the heat is transferred from a hot surface to a cold surface, as shown in Fig. 10.4.

As a matter of fact, there will be a thin film of air on both the hot as well as cold faces of the wall, which will act as transition layers adjact to the wall surface and through which the heat also has to flow in addition to the wall as shown in Fig. 10.4. Let A and B be the effective film of air for the heat flow.

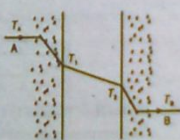


Fig. 10.4

Let A = Surface area of the wall,

x = Thickness of the wall,

k = Thermal conductivity of the wall material,

T_A and T_B = Temperatures at the end of two thin films of air A and B respectively,

h_A and h_B = Film coefficient of heat transfer for A and B respectively,

U = Overall coefficient of heat transfer.

We know that the rate of heat flow through air film A,

$$Q = h_A\, A(T_A - T_1) \quad \text{or} \quad T_A - T_1 = \frac{Q}{h_A\, A} \qquad ...(i)$$

Similarly, rate of heat flow through the wall,

$$Q = \frac{k\,A(T_1 - T_2)}{x} \quad \text{or} \quad T_1 - T_2 = \frac{Q\,x}{k\,A} \qquad ...(ii)$$

and rate of heat flow through the air film B,

$$Q = h_B\, A(T_2 - T_B) \quad \text{or} \quad T_2 - T_B = \frac{Q}{h_B\, A} \qquad ...(iii)$$

Adding equations (*i*), (*ii*) and (*iii*),

$$(T_A - T_B) = \frac{Q}{A}\left[\frac{1}{h_A} + \frac{x}{k} + \frac{1}{h_B}\right] \quad \text{or} \quad Q = \frac{A\,(T_A - T_B)}{\left[\frac{1}{h_A} + \frac{x}{k} + \frac{1}{h_B}\right]} \qquad ...(iv)$$

We know that rate of heat flow,

$$Q = UA\,(T_A - T_B) \qquad ...(v)$$

Equating equations (*iv*) and (*v*),

$$U = \frac{1}{\left[\frac{1}{h_A} + \frac{x}{k} + \frac{1}{h_B}\right]}$$

10.9 Logarithmic Mean Temperature Difference

The logarithmic mean temperature difference (LMTD) for a heat exchanger is given by

$$t_m = \frac{\Delta t_1 - \Delta t_2}{\log_e \Delta t_1 / \Delta t_2}$$

where Δt_1 and Δt_2 are temperature differences between the hot and cold fluids at entrance and exit.

10.10 Heat Exchanger

A device used for transfering heat from fluid to another is called a heat exchanger. Its use is made in radiators in automobile, intercoolers and pre heaters, condensers and boilers in steam plants, condensers and evaporators in refrigeration and air conditioning units. The following two types of heat exchangers are common in use :

1. Parallel flow heat exchanger ; and 2. Counter-current flow heat exchanger.

In parallel flow heat exchangers, the fluids flow in the same direction. The temperature difference is maximum at inlet and consequently the rate of flow of heat and the rate of decrease of temperature are maximum here.

In counter current flow heat exchanger, the fluids flow in the opposite directions. The heat transfer takes place between the fluids at the moment when each is in its coldest state or when each is in its hottest state. The average temperature between the two fluids is greater than in parallel flow heat exchanger.

10.11 Forced Convection

In forced convection, the film coefficient of heat transfer (h) depends upon coefficient of absolute viscosity (μ), density of fluid (ρ), thermal conductivity (k), specific heat at constant pressure (c_p), temperature difference between the surface and the fluid (T), velocity of the fluid (v) and the characteristic linear dimension (l). From dimensional analysis, we may write them in dimensionless group as

$$\frac{hl}{k} = f\left[\left(\frac{c_p\mu}{k}\right)\left(\frac{\rho v l}{\mu}\right)\right]$$

The dimensionless group

$\frac{hl}{k}$ is called Nusselt number (N_N),

$\frac{c_p\mu}{k}$ is called Prandtl number (P_N), and $\frac{\rho v l}{\mu}$ is called Reynolds number (R_N).

It may be noted that each dimensionless number in the above equation is the function of some properties of the fluid. The properties of fluid change with temperature. A common procedure is to calculate the properties at a mean film temperature (T_F) which is given by

$$T_F = \frac{T_B + T_W}{2}$$

where T_B = Mean bulk temperature, and

T_W = Wall surface temperature.

10.12 Free Convection

In the free convection heat transfer, the motion of the fluids is caused by the buoyancy forces arising from variation in density of the fluid with the temperature. Such cases normally occur when heating or cooling of the body takes place by complete or partial immersion in the fluid which is an undisturbed fluid otherwise.

10.13 Radiation

The term radiation is applied to the kinds of processes which transmit energy by means of electromagnetic waves. The amount of radiation mainly depends upon the nature, temperature and type of surface of the body. When the radiations are falling on a body, three things happen, *i.e.* a part of the radiations are absorbed by the body, a part of the radiations are reflected and the remaining radiations are transmitted through the body. If Q_i is the total incident radiations, then

$$Q_i = Q_a + Q_r + Q_t$$

where Q_a = Incident radiation absorbed,

Q_r = Incident radiation reflected, and

Q_t = Incident radiation transmitted.

The above equation may be written as

$$1 = \frac{Q_a}{Q_i} + \frac{Q_r}{Q_i} + \frac{Q_t}{Q_i} = \alpha + \rho + \tau$$

α = Absorptivity. It is the ratio of incident radiation absorbed to the total incident radiations,

ρ = Reflectivity. It is the ratio of incident radiation reflected to the total incident radiations, and

τ = Transmitivity. It is the ratio of incident radiation transmitted to the total incident radiations.

The bodies may be black, white, transparent or opaque body.

A black body is one which absorbs all the incident radiations. Thus for a black body, $\alpha = 1$, $\rho = 0$ and $\tau = 0$.

A white body is one which reflects all the incident radiations. Thus, for a white body, $\rho = 1$, $\alpha = 0$ and $\tau = 0$.

A transparent body is one which transmits all the incident radiations. Thus, for a transparent body $\tau = 1$, $\rho = 0$, and $\alpha = 0$.

An opaque body is one which does not transmit the incident radiation. Thus for an opaque body, $\tau = 0$ and $\alpha + \rho = 1$.

10.14 Total and Monochromatic Emissive Power

The total amount of radiation emitted by a body per unit area and time is called *total emissive power* (E). It is expressed in W / m^2.

At any given temperature, the amount of radiation emitted per unit wavelength varies at different wavelengths. For this purpose, the *monochromatic (spectral) emissive power* (E_λ) of the surface is used. It is defined as the rate of energy radiated per unit area of the surface per unit wavelength. The total emissive power is given by

$$E = \int_0^\infty E_\lambda \, . \, d\lambda$$

10.15 Stefan Boltzman Law

According to Stefan Boltzman law, the emissive power of a black body (*i.e.* the total radiation emitted by a black body per unit area and time is directly proportional to the fourth power of the absolute temperature. Mathematically, emissive power of a black body,

$$E_b = \sigma \, T^4$$

where σ = Stefan Boltzman constant = 5.67×10^{-8} W / m^2 K^4

10.16 Kirchhoff's Law

According to Krichhoff's law, the ratio of the emissive power and absorptive power of all bodies is the same and is equal to the emissive power of a perfectly black body.

10.17 Wien's Law

According to Wien's law, the product of wavelength (λ_{max}) corresponding to the maximum monochromatic emissive power and the absolute temperature of a black body (T) is constant. In other words,

$$\lambda_{max} \times T = \text{Constant}$$

The value of constant is equal to 2900 μmK.

10.18 Emissivity

It is defined as the ratio of total emissive power of a body to the total emissive power of a black body. It may be noted that at thermal equilibrium, the emissivity and absorptivity of a body are the same.

10.19 Grey Body

A grey body is defined as one whose absorptivity of a surface does not vary with temperature and wavelength of the incident radiation. In other words, if the ratio of emission of a body to that of a black body at a given temperature is constant for all wavelengths, then the body is called a *grey body*.

10.20 Refrigeration

The term refrigeration may be defined as the process of removing heat from a substance under controlled conditions. It also includes the process of reducing and maintaining the temperature of a body below the temperature of its surroundings. In other words, the refrigeration means a continued extraction of heat from a body whose temperature is already below the temperature of its surroundings.

The practical unit of refrigeration is expressed in terms of 'tonne of refrigeration' (briefly written as TR). A tonne of refrigeration is defined as the amount of refrigeration effect produced by the uniform melting of one tonne (1000 kg) of ice from and at 0° C in 24 hours.

Since the latent heat of ice is 335 kJ / kg, therefore one tonne of refrigeration,

$$1 \text{ TR} = 1000 \times 335 \text{ kj in 24 hours} = \frac{1000 \times 335}{24 \times 60} = 232.6 \text{ kJ/min}$$

In actual practice, one tonne of refrigeration is taken as equivalent to 210 kJ / min or 3.5 kW (*i.e.* 3.5 kJ / s).

10.21 Coefficient of Performance of Refrigerator

Theoretically, a *refrigerator* is a reversed heat engine or a heat pump which pumps heat from a cold body and delivers it to a hot body. The substance which works in a heat pump to extract heat from a cold body and deliver it to a hot body, is called a *refrigerant*.

The coefficient of performance (briefly written as C.O.P.) is the ratio of heat extracted in the refrigerator to the workdone on the refrigerant. It is also known as theoretical coefficient of performance.

Notes : 1. The coefficient of performance is the reciprocal of the efficiency of a heat engine. It is thus obvious that the value of C.O.P. is always greater than unity.

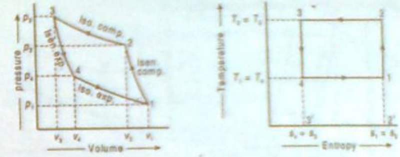
2. The ratio of the actual C.O.P. to the theoretical C.O.P. is known as relative coefficient of performance. Mathematically,

$$\text{Relative C.O.P.} = \frac{\text{Actual C.O.P.}}{\text{Theoretical C.O.P.}}$$

10.22 Air Refrigerator Working on Reversed Carnot Cycle

In refrigerating systems, the Carnot cycle considered is the reversed Carnot cycle. We know that a heat engine working on Carnot cycle has the highest possible efficiency. Similarly, a refrigerating system working on the reversed Carnot cycle, will have the maximum possible coefficient of performance. We also know that it is not possible to make an engine working on the Carnot cycle. Similarly, it is also not possible to make a refrigerating machine working on the reversed Carnot cycle. However, it is used as the ultimate standard of comparison.

A reversed Carnot cycle using air as working medium (or refrigerant) is shown on p–v and T–s diagrams in Fig. 10.5 (*a*) and (*b*) respectively.



(*a*) p-v diagram. (*b*) T-s diagram.

Fig. 10.5

The four processes of the cycle are as follows :

1. *Isentropic compression process.* This process is represented by 1-2 on p-v and T-s diagrams. During this process, no heat is absorbed or rejected by the air.

2. *Isothermal compression process.* This process is represented by 2-3 on p-v and T-s diagrams. During this process, heat is rejected by the air. We know that the heat rejected by the air during isothermal compression per kg of air,

$$q_{2-3} = \text{Area } 2\text{-}3\text{-}3'\text{-}2'$$
$$= T_3 (s_2 - s_3) = T_2 (s_2 - s_3)$$

3. *Isentropic expansion process.* This process is represented by 3-4 on p-v and T-s diagrams. During this process, no heat is absorbed or rejected by the air.

4. *Isothermal expansion process.* This process is represented by 4-1 on p-v and T-s diagrams. During this process, heat is absorbed by the air. We know that the heat absorbed by the air (or heat extracted from the cold body) during isothermal expansion per kg of air,

$$q_{4-1} = \text{Area } 4\text{-}1\text{-}2'\text{-}3'$$
$$= T_4 (s_1 - s_4) = T_4 (s_2 - s_3) = T_1 (s_2 - s_3)$$

We know that workdone during the cycle per kg of air

$$= {}^*\text{Heat rejected} - \text{Heat absorbed}$$
$$= T_2 (s_2 - s_3) - T_1 (s_2 - s_3) = (T_2 - T_1)(s_2 - s_3)$$

∴ Coefficient of performance of the refrigeration system working on reversed Carnot cycle,

$$(\text{C.O.P.})_R = \frac{\text{Heat absorbed}}{\text{Workdone}} = \frac{T_1 (s_2 - s_3)}{(T_2 - T_1)(s_2 - s_3)} = \frac{T_1}{T_2 - T_1}$$

The C.O.P of the reversed Carnot cycle may be improved by

(*a*) decreasing the higher temperature (*i.e.* the temperature of hot body, T_2), or

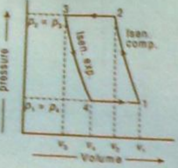
(*b*) increasing the lower temperature (*i.e.* the temperature of cold body, T_1).

Note : The C.O.P of a domestic refrigerator is less than the C.O.P. of a domestic air conditioner.

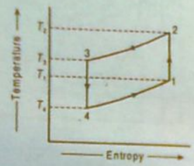
* In a refregerating machine, heat rejected is more than heat absorbed.

10.23 Air Refrigerator Working on a Bell-Coleman Cycle (or Reversed Brayton or Joule Cycle)

The Bell-Coleman cycle is a modification of reversed Carnot cycle. The cycle is shown on p–v and T–s diagrams in Fig. 10.6 (a) and (b) respectively.



(a) p-v diagram.



(b) T-s diagram.

Fig. 10.6

The four processes of the cycle are as follows :

1. *Isentropic compression process.* This process is represented by 1-2 on p-v and T-s diagrams. During this process, no heat is absorbed or rejected by the air.

2. *Constant pressure cooling process.* This process is represented by 2-3 on p-v and T-s diagrams. During this process, heat is rejected by the air. We know that heat rejected by the air during constant pressure per kg air,

$$q_{2-3} = c_p (T_2 - T_3)$$

3. *Isentropic expansion process.* This process is represented by 3-4 on p-v and T-s diagrams. During this process, no heat is absorbed or rejected by the air.

4. *Constant pressure expansion process.* This process is represented by 4-1 on p-v and T-s diagrams. During this process, heat is absorbed by the air. We know that the heat absorbed by the air (or heat extracted from the refrigerator) during constant pressure expansion process per kg of air,

$$q_{4-1} = c_p (T_1 - T_4)$$

We know that workdone during the cycle per kg of air

$$= \text{Heat rejected} - \text{Heat absorbed}$$

$$= c_p (T_2 - T_3) - c_p (T_1 - T_4)$$

$\therefore$ Coefficient of performance,

$$\text{C.O.P.} = \frac{\text{Heat absorbed}}{\text{Workdone}} = \frac{c_p (T_1 - T_4)}{c_p (T_2 - T_3) - c_p (T_1 - T_4)}$$

$$= \frac{T_1 - T_4}{(T_2 - T_3) - (T_1 - T_4)} = \frac{T_4\left(\dfrac{T_1}{T_4} - 1\right)}{T_3\left[\dfrac{T_2}{T_3} - 1\right] - T_4\left[\dfrac{T_1}{T_4} - 1\right]} \quad \text{...}(i)$$

We know that for isentropic compression process 1-2,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \quad \text{...}(ii)$$

Similarly, for isentropic expansion process 3-4,

$$\frac{T_3}{T_4} = \left(\frac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}} \quad \text{...}(iii)$$

Since $p_2 = p_3$ and $p_1 = p_4$, therefore, from equations (ii) and (iii),

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \quad \text{or} \quad \frac{T_2}{T_3} = \frac{T_1}{T_4} \quad \text{...}(iv)$$

Now substituting these values in equation (i), we get,

$$\text{C.O.P.} = \frac{T_4}{T_3 - T_4} = \frac{T_4}{T_4\left(\dfrac{T_3}{T_4} - 1\right)} = \frac{1}{\left(\dfrac{p_3}{p_4}\right)^{\frac{\gamma-1}{\gamma}} - 1}$$

$$= \frac{1}{\left(\dfrac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} - 1} = \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}} - 1}$$

where $\quad r_p =$ Compression or expansion ratio $= \dfrac{p_2}{p_1} = \dfrac{p_3}{p_4}$

10.24 Vapour Compression Refrigeration System

A schematic diagram of a simple vapour compression refrigeration system is shown in Fig. 10.7. In this system, a suitable working substance (known as refrigerant) such as ammonia, carbon dioxide, sulphur dioxide or Freon 12 is used. It consists of the following five essential parts :

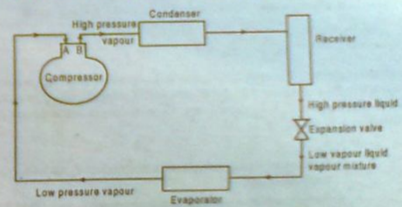


Fig. 10.7

1. *Compressor.* The low pressure and temperature vapour refrigerant from evaporator is drawn into the compressor through the inlet or suction valve A, where it is compressed to a high pressure and temperature. This high pressure and temperature vapour refrigerant is discharged into the condenser through the delivery or discharge valve B.

2. *Condenser.* The condenser or cooler consists of coils of pipe in which the high pressure and temperature vapour refrigerant is cooled and condensed.

3. *Receiver.* The condensed liquid refrigerant from the condenser is stored in a vessel known

as receiver from where it is supplied to the evaporator through the expansion valve or refrigerant control valve.

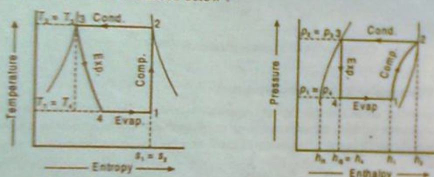
4. *Expansion valve*. The expansion valve allows the liquid refrigerant under high pressure and temperature to pass at a controlled rate after reducing its pressure and temperature.

5. *Evaporator*. An evaporator consists of coils of pipe in which the liquid-vapour refrigerant at low pressure and temperature is evaporated and changed into vapour refrigerant at low pressure and temperature.

Note : In any compression refrigeration system, there are two different pressure conditions. One is called the *high pressure side* and the other is known as *low pressure side*. The high pressure side includes the discharge line (*i.e.*, piping from delivery valve *B* to the condenser), receiver and expansion valve. The low pressure side includes the evaporator, piping from the expansion valve to the evaporator and the suction line (*i.e.* piping from the evaporator to the suction valve *A*).

10.25 Vapour Compression Cycle

A vapour compression cycle with dry saturated vapour after compression is shown on *T-s* and *p-h* diagrams in Fig. 10.8. It essentially consists of compression, condensation, expansion or throttling and evaporation as discussed below :



(*a*) *T-s* diagram. (*b*) *p-h* diagram.

Fig. 10.8

1. *Compression process*. The vapour refrigerant at low pressure and temperature from the evaporator is drawn into the compressor where it is compressed isentropically. The pressure and temperature rises from p_1 to p_2 and T_1 to T_2 respectively. The workdone during isentropic compression per kg of refrigerant is given by

$$w = h_2 - h_1$$

where h_1 = Enthalpy of vapour refrigerant at temperature T_1, *i.e.* at suction of the compressor, and

h_2 = Enthalpy of vapour refrigerant at temperature T_2, *i.e.* at discharge of the compressor.

2. *Condensing process*. The high pressure and temperature vapour refrigerant from the compressor is passed through the condenser where it is completely condensed at constant pressure and temperature. The vapour refrigerant is changed into liquid refrigerant.

3. *Expansion process*. The liquid refrigerant at high pressure and temperature is expanded by throttling process through the expansion valve to a low pressure and temperature. Some of the liquid refrigerant evaporates as it passes through the expansion valve, but the greater portion is vaporised in the evaporator.

4. *Vaporising process*. The liquid-vapour mixture of the refrigerant is evaporated and changed into vapour refrigerant. During evaporation, the liquid-vapour refrigerant absorbs its latent heat of vaporisation from the medium (air, water or brine) which is to be cooled. This heat which is absorbed by the refrigerant is called *refrigerating effect* (R_E).

The refrigerating effect or the heat absorbed or extracted by the liquid-vapour refrigerant during evaporation per kg of refrigerant is given by

$$R_E = h_1 - h_4 = h_1 - h_{f3}$$

where h_{f3} = Enthalpy of liquid refrigerant leaving the condenser.

We know that coefficient of performance,

$$\text{C.O.P.} = \frac{\text{Refrigerating effect}}{\text{Workdone}} = \frac{h_1 - h_4}{h_2 - h_1} = \frac{h_1 - h_{f3}}{h_2 - h_1}$$

10.26 Undercooling or Subcooling of Refrigerant

Sometimes, the refrigerant after condensation process is cooled below the saturation temperature before expansion by throttling. Such a process is called *undercooling* or *subcooling* of the refrigerant. The ultimate effect of undercooling is to increase the value of coefficient of performance.

The process of undercooling is generally brought about by circulating more quantity of cooling water through the condenser or by using water colder than the main circulating water. Sometimes, this process is also brought about by employing a heat exchanger. In actual practice, the refrigerant is superheated after compression and undercooled before throttling.

10.27 Vapour Absorption Refrigeration System

It is one of the oldest method of producing refrigerating effect. This system may be used in both the domestic and large industrial refrigerating plants. The refrigerant commonly used in this system is ammonia. The vapour absorption system uses heat energy, instead of mechanical energy as in vapour compression systems, in order to change the conditions of the refrigerant required for the operation of the refrigeration cycle.

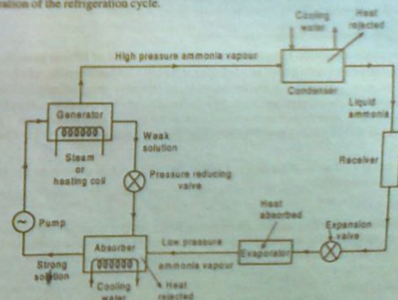


Fig. 10.9

The vapour absorption system as shown in Fig. 10.9, consists of an absorber, a pump, a generator and a pressure reducing valve.

These components perform the same function as that of a compressor in vapour compression system. In the vapour absorption system, the vapour refrigerant from the evaporator is drawn into an absorber where it is absorbed by weak solution of the refrigerant forming a strong solution. This strong solution is pumped to the generator where it is heated by some external source. During the heating process, the vapour refrigerant is driven off by the solution and enters into the condenser where it is liquified. The liquid refrigerant then flows into the evaporator and thus the cycle is completed.

The C.O.P. of a vapour absorption system is given by

$$\text{C.O.P.} = \frac{T_E}{T_G}\left(\frac{T_G - T_C}{T_C - T_E}\right)$$

where T_G = Temperature at which heat is given to the generator,

T_C = Temperature at which heat is discharged to the cooling water from the condenser and absorber, and

T_E = Temperature at which heat is absorbed in the evaporator.

10.28 Domestic Electrolux (Ammonia Hydrogen) Refrigerator

The main purpose of domestic electrolux refrigerator is to eliminate the pump so that in the absence of moving parts, the machine becomes noise-less. This type of refrigerator is also called *three-fluids absorption system*. The three fluids used in this system are ammonia, hydrogen and water. The ammonia is used as a refrigerant because it possesses most of the desirable properties. The hydrogen being the lightest gas, is used to increase the rate of evaporation of the liquid ammonia passing through the evaporator. The hydrogen is also non-corrosive and insoluble in water. The water is used as a solvent because it has the ability to absorb ammonia readily.

The C.O.P. of this type of refrigerator is given by the ratio of heat absorbed in the evaporator to the heat supplied in the generator.

10.29 Lithium Bromide Absorption Refrigeration System

The lithium bromide absorption refrigeration system uses a solution of lithium bromide in water. In this system, the water is being used as a refrigerant whereas lithium bromide, which is a highly hydroscopic salt, as an absorbent. The lithium bromide solution has a strong affinity for water vapour because of its very low vapour pressure. Since lithium bromide solution is corrosive, therefore inhibitors should be added in order to protect the metal parts of the system against corrosion. This system is very popular for air conditioning in which low refrigeration temperatures (not below 0° C) are required.

Note : Since water is used as a refrigerant in this system, therefore, the refrigeration temperature must be kept above the freezing point of water (0° C).

10.30 Refrigerants

The refrigerant is a heat carrying medium which during their cycle (*i.e.* compression, condensation, expansion and evaporation) in the refrigeration system absorb heat from a low temperature system and discard the heat so absorbed to a higher temperature system. A good refrigerant should have the following properties :

1. Low boiling point,
2. High critical temperature,

3. High latent heat of vaporisation,
4. Low specific heat of liquid,
5. Low specific volume of vapour,
6. Non-corrosive to metal,
7. Non-flammable and non-explosive,
8. Non-toxic,
9. Low cost,
10. Easy to liquify at moderate pressure and temperature,
11. Easy of locating leaks by odour or suitable indicator, and
12. Mixes well with oil.

The following refrigerants are mostly used :

(*a*) *R* - 11 (CCl_3F). It is stable, non-flammable and non-toxic. It is considered to be a low-pressure refrigerant. It has a low side pressure of 0.202 bar at – 15° C, and high side pressure of 1.2606 bar at 30°C. The latent heat at –15°C is 195 kJ / kg. The boiling point at atmospheric pressure is 23.77° C. Due to its low operating pressures, this refrigerant is exclusively used in large centrifugal compressor systems of 200 TR and above. The leaks may be detected by using a soap solution, a halide torch or by using an electronic detector. The cylinder colour code for *R* - 11 is orange.

(*b*) *R* - 12 (CCl_2F). It is a very popular refrigerant. It is a colourless, almost odourless liquid with boiling point of – 29° C at atmospheric pressure. It is non-toxic, non-corrosive, non-irritating and non-flammable. It has a relatively low latent heat value which is an advantage in small refrigerating machines. This refrigerant is used in many different types of industrial and commercial applications such as refrigerators, freezers, water coolers, room and window air conditioning units etc. Its principal use is found in reciprocating and rotary compressors, but its use in centrifugal compressors for large commercial air conditioning is increasing.

R - 12 has a pressure of 0.82 bar at – 15° C and a pressure of 6.4 bar at 30° C. The latent heat of *R* - 12 at – 15° C is 159 kJ / kg. The leak may be detected by soap solution, halide torch or an electronic leak detector. The refrigerant is available in a variety of cylinder sizes and the cylinder colour code is white.

(*c*) *R* - 22 ($CHClF_2$). It has also been successfully used in air conditioning units and in household refrigerators. It is used with reciprocating and centrifugal compressors. It is not necessary to use *R* - 22 at below atmospheric pressures in order to obtain the low temperatures.

The boiling point is – 41° C at atmospheric pressure. It has a latent heat of 216.5 kJ / kg at – 15° C. The normal head pressure at 30° C is 10.88 bar. This refrigerant is stable and is non-toxic, non-corrosive, non-irritating and non-flammable. The evaporator pressure of this refrigerant at – 15° C is 1.92 bar. This refrigerant has good solubility in oil down to – 9° C. However, the oil remains fluid enough to flow down the suction line at temperatures as low as – 40° C. The oil will begin to separate at this point. Since oil is lighter, therefore it will collect on the surface of the liquid refrigerant. The leaks may be detected with a soap solution, a halide torch or with an electronic leak detector. The cylinder colour code for R-22 is green.

(*d*) *Ammonia* (NH_3). It is one of the oldest and most widely used of all the refrigerants. Its greatest application is found in large and commercial reciprocating compression systems where high toxicity is secondary. It is also widely used in absorption systems. It is a chemical compound of nitrogen and hydrogen and under ordinary conditions, it is a colourless gas. Its boiling point at atmospheric pressure is – 33.3° C and its melting point from the solid is – 78° C. The low boiling point makes it possible to have refrigeration at temperature considerably below 0° C without using pressures below atmospheric in the evaporator. Its latent heat of vaporisation at – 15° C is 1315 kJ / kg. Thus, large refrigerating effects are possible with relatively small sized machinery. The condenser pressure at 30° C is 10.78 bar. The condensers for ammonia are usually of water cooled type. This refrigerant is used in large compression machines using reciprocating compressors and in many absorption type systems. The use of this refrigerant is extensively found in cold storage, warehouse plants, ice cream manufacture, ice manufacture, beer manufacture, food freezing plants etc.

The leaks of this refrigerant may be quickly and easily detected by the use of burning sulphur candle which in the presence of ammonia forms white fumes of ammonium sulphite.

(*e*) *Carbon dioxide* (CO_2). The principal refrigeration use of carbon dioxide is same as that of dry ice. It is non-toxic, non-irritating and non-flammable. The boiling point of this refrigerant is so extremely low (– 73.6° C) that at – 15° C, a pressure of well over 20.7 bar is required to prevent its evaporation. At a condenser temperature of + 30° C, a pressure of approximately 70 bar is required to liquify the gas. Its critical temperature is 31° C and triple point is – 56.6° C. Due to its high operating pressure, the compressor of a carbon dioxide refrigerator unit is very small even for a comparatively large refrigerating capacity. However, because of its low efficiency as compared to other common refrigerants, it is seldom used in household units but is used in some industrial applications and aboard ships.

(*f*) *Sulphur dioxide* (SO_2). This refrigerant is produced by the combustion of sulphur in air. In the former years, it was widely used in household and small commercial units. The boiling point of sulphur dioxide is – 10° C at atmospheric pressure. The condensing pressure varies between 4.1 bar and 6.2 bar under normal operating conditions. The latent heat of sulphur dioxide at – 15° C is 396 kJ / kg. It is a very stable refrigerant with a high critical temperature and it is non-flammable and non-explosive. It has a very unpleasant and irritating odour. This refrigerant is not injurious to food and is used commercially as a ripener and preservative of foods. It is however, extremely injurious to flowers, plants and shrubbery.

The leaks in the system with sulphur dioxide may be easily detected by means of soap solution or ammonia swab. A dense white smoke forms when sulphur dioxide and ammonia fumes come in contact.

10.31 Air Conditioning

The air conditioning is that branch of engineering science which deals with the study of conditioning of air *i.e.* supplying and maintaining desirable internal atmospheric conditions for human comfort, irrespective of external conditions. The following are the four important factors for comfort air conditioning :

1. Temperature of air, 2. Humidity of air, 3. Purity of air, and 4. Motion of air.

10.32 Psychrometry

The psychrometry is that branch of engineering science which deals with the study of moist air, *i.e.* dry air mixed with water vapour or humidity. The following psychrometric terms may be clearly understood :

1. *Dry air.* The pure dry air is a mixture of number of gases such as nitrogen, oxygen, carbon dioxide, hydrogen, argon, neon, helium etc. but the nitrogen and oxygen have the major portion of the combination.

2. *Moist air.* It is a mixture of dry air and water vapour. The amount of water vapour, present in the air, depends upon the absolute pressure and temperature of the mixture.

3. *Saturated air.* It is a mixture of dry air and water vapour, when the air has diffused the maximum amount of water vapour into it.

4. *Degree of saturation.* It is the ratio of actual mass of water vapour in a unit mass of dry air to the mass of water vapour in the same mass of dry air when it is saturated at the same temperature and pressure.

5. *Humidity.* It is the mass of water vapour present in 1 kg of dry air, and is generally expressed in terms of gram per kg of dry air (g / kg of dry air). It is also called *specific humidity* or *humidity ratio.*

6. *Absolute humidity.* It is the mass of water vapour present in 1 m^3 of dry air, and is generally expressed in terms of gram per cubic metre of dry air (g / m^3 of dry air).

7. *Relative humidity.* It is the ratio of actual mass of water vapour in a given volume of moist air to the mass of water vapour in the same volume of saturated air at the same temperature and pressure.

8. *Dry bulb temperature.* It is the temperature of air recorded by a thermometer, when it is not affected by the moisture present in the air.

9. *Wet bulb temperature.* It is the temperature of air recorded by a thermometer, when its bulb is surrounded by a wet cloth exposed to the air. Such a thermometer is called wet bulb thermometer.

10. *Wet bulb depression.* It is the difference between dry bulb temperature and wet bulb temperature at any point. The wet bulb depression indicates relative humidity of the air.

11. *Dew point temperature.* It is the temperature of air recorded by a thermometer, when the moisture (water vapour) present in it begins to condense. In other words, the dew point temperature is the saturation temperature corresponding to the partial pressure of water vapour.

Note : For saturated air, the dry bulb temperature, wet bulb temperature and dew point temperature is same.

12. *Dew point depression.* It is the difference between the dry bulb temperature and dew point temperature of air.

10.33 Dalton's Law of Partial Pressures

It states, "*The total pressure exerted by the mixture of air and water vapour is equal to the sum of the pressures, which each constituent would exert, if it occupied the same space by itself*". Or in other words, the total pressure exerted by air and water vapour mixture is equal to the barometric pressure. Mathematically, barometric pressure of the mixture,

$$p_b = p_a + p_v$$

where p_a = Partial pressure of dry air, and

p_v = Partial pressure of water vapour.

10.34 Psychrometric Relations

The following psychrometric relations are important :

1. *Specific humidity, humidity ratio or moisture content.* It is the mass of water vapour present in 1 kg of dry air (in the air-vapour mixture) and is generally expressed in g / kg of dry air. It may also be defined as the ratio of mass of water vapour to the mass of dry air in a given volume of the air-vapour mixture. Mathematically, humidity ratio,

$$W = 0.622 \times \frac{p_v}{p_b - p_v}$$

2. *Degree of saturation or percentage humidity.* It is the ratio of actual mass of water vapour in a unit mass of dry air to the mass of water vapour in the same mass of dry air when it is saturated at the same temperature (dry bulb temperature). In other words, it may be defined as the ratio of actual

specific humidity to the specific humidity of saturated air at the same dry bulb temperature. Mathematically, degree of saturation,

$$\mu = \frac{p_v}{p_s}\left[\frac{p_b - p_s}{p_b - p_v}\right]$$

where p_s = Partial pressure of air corresponding to saturation temperature (*i.e.* dry bulb temperature).

3. *Relative humidity.* It is the ratio of actual mass of water vapour in a given volume of moist air to the mass of water vapour in the same volume of saturated air at the same temperature and pressure. Mathematically, relative humidity,

$$\phi = \frac{\mu}{1-(1-\mu)\frac{p_s}{p_b}}$$

Note : For saturated air, the relative humidity is 100%.

4. *Pressure of water vapour.* According to Carrier's equation, the partial pressure of water vapour,

$$p_v = p_w - \frac{(p_b - p_w)(t_d - t_w)}{1544 - 1.44\, t_w}$$

where p_w = Saturation pressure corresponding to wet bulb temperature (from steam tables),

p_b = Barometric pressure,

t_d = Dry bulb temperatue, and

t_w = Wet bulb temperature.

5. *Vapour density or absolute humidity.* It is the mass of water vapour present in 1 m^3 of dry air.

6. *Thermodynamic wet bulb temperature or adiabatic saturation temperature.* It is the temperature at which the air can be brought to saturation state, adiabatically, by the evaporation of water into the flowing air.

10.35 Psychrometric Chart

It is a graphical representation of the various thermodynamic properties of moist air. The psychrometric chart is very useful for finding out the properties of air (which are required in the field of air conditioning) and eliminate lot of calculations. This chart is normally drawn for standard atmospheric pressure of 760 mm of Hg (or 1.01325 bar).

In a psychrometric chart, dry bulb temperature is taken as abscissa and specific humidity (*i.e.* moisture contents) as ordinate, as shown in Fig. 10.10. The saturation curve is drawn by plotting the various saturation points at corresponding dry bulb temperatures. The saturation curve represents 100% relative humidity at various dry bulb temperatures. It also represents the wet bulb and dew point temperatures. The psychrometric chart contains the following important lines :

1. *Dry bulb temperature lines.* These lines are vertical *i.e.* parallel to the ordinate and uniformly spaced.

2. *Specific humidity or moisture content lines.* These lines are horizontal *i.e.* parallel to the abscissa and uniformly spaced.

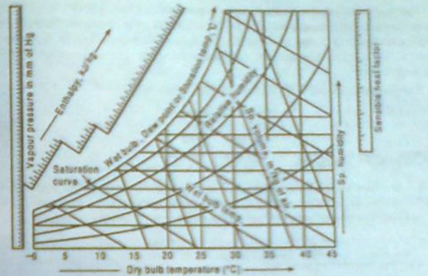


Fig. 10.10

3. *Dew point temperature lines.* These lines are horizontal *i.e.* parallel to the abscissa and non-uniformly spaced. At any point on the saturation curve, the dry bulb and dew point temperatures are equal.

4. *Wet bulb temperature lines.* These lines are inclined straight lines and non-uniformly spaced. At any point on the saturation curve, the dry bulb and wet bulb temperatures are equal.

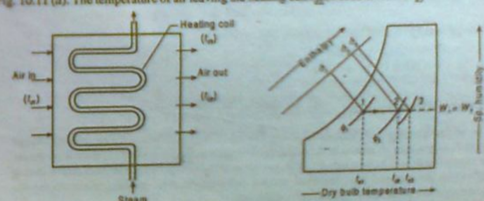
5. *Specific volume lines.* These lines are obliquely inclined straight lines and uniformly spaced.

6. *Relative humidity lines.* These lines are curved lines and follow the saturation curve. The saturation curve represents 100% relative humidity.

10.36 Psychrometric Processes

The various psychrometric processes involved in air conditioning to vary the psychrometric properties of air according to the requirement are as follows:

1. *Sensible heating.* The heating of air, without any change in its specific humidity, is known as sensible heating. Let air at temperature t_{d1} passes over a heating coil of temperature t_{d3} as shown in Fig. 10.11 (*a*). The temperature of air leaving the heating coil t_{d2} will be less than t_{d3}.



(*a*) Psychrometric process. (*b*) Psychrometric chart.

Fig. 10.11

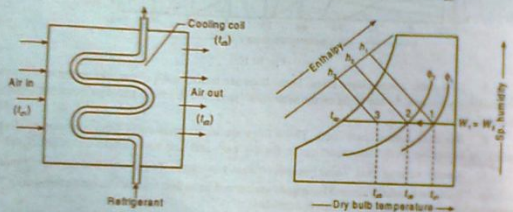
The process of sensible heating, on the psychrometric chart, is shown by a horizontal line 1-2 extending from left to right as shown in Fig. 10.11 (*b*). The point 3 represents the surface temperature of the heating coil. It may be noted that during sensible heating, specific humidity remains constant (*i.e.* $W_1 = W_2$), dry bulb temperature increases from t_{d1} to t_{d2}, and relative humidity decreases from ϕ_1 to ϕ_2.

The by-pass factor (BPF) for the heating coil is given by

$$BPF = \frac{t_{d3} - t_{d2}}{t_{d3} - t_{d1}}$$

and efficiency of the heating coil, $\quad \eta_H = 1 - BPF = \frac{t_{d2} - t_{d1}}{t_{d3} - t_{d1}}$

2. *Sensible cooling.* The cooling of air, without any change in its specific humidity, is known as sensible cooling. Let air at temperature t_{d1} passes over a cooling coil of temperature t_{d3}, as shown in Fig. 10.12 (*a*). The temperature of air leaving the cooling coil (t_{d2}) will be more than t_{d3}.



(*a*) Psychrometric process. (*b*) Psychrometric chart.

Fig. 10.12

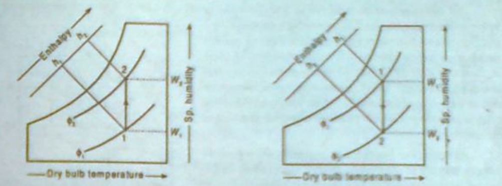
The process of sensible cooling, on the psychrometric chart, is shown by a horizontal line 1-2 extending from right to left, as shown in Fig. 10.12 (*b*). The point 3 represents the surface temperature of the cooling coil. It may be noted that during sensible cooling, specific humidity remains constant (*i.e.* $W_1 = W_2$), dry bulb temperature decreases from t_{d1} to t_{d2} and relative humidity increases from ϕ_1 to ϕ_2.

The by-pass factor (BPF) for the cooling coil is given by

$$BPF = \frac{t_{d2} - t_{d3}}{t_{d1} - t_{d3}}$$

and efficiency of the cooling coil, $\quad \eta_H = 1 - BPF = \frac{t_{d1} - t_{d2}}{t_{d1} - t_{d3}}$

3. *Humidification and Dehumidification.* The addition of moisture to the air, without change in its dry bulb temperature, is known as humidification. Similarly, the removal of moisture from the air, without change in its dry bulb temperature is known as dehumidification. The heat added during humidification process and heat removed during dehumidification process is shown on the psychrometric chart in Fig. 10.13 (*a*) and (*b*) respectively.



(*a*) Humidification (*b*) Dehumidification

Fig. 10.13

It may be noted that in humidification, the relative humidity increases from ϕ_1 to ϕ_2 and specific humidity also increases from W_1 to W_2. Similarly, in dehumidification, the relative humidity decreases from ϕ_1 to ϕ_2 and specific humidity also decreases from W_1 to W_2.

4. *Cooling and Dehumidification.* This process is generally used in summer air conditioning to cool and dehumidify the air. The air is passed over a cooling coil or through a cold water spray. In this process, the dry bulb temperature as well as the specific humidity of air decreases. The final relative humidity of the air is generally higher than that of the entering air. The dehumidification of air is only possible when the effective surface temperature of the cooling coil (*i.e.* t_{d4}) is less than the dew point temperature of the air entering the coil (*i.e.* t_{dp1}). The effective surface temperature of the coil is known as *apparatus dew point* (briefly written as ADP).

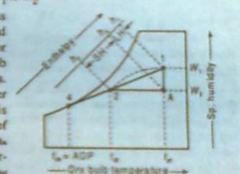


Fig. 10.14

The cooling and dehumidification process shown in Fig. 10.14.

Under ideal conditions, the dry bulb temperature of the air leaving the cooling coil (*i.e.* t_{d4}) should be equal to the surface temperature of the cooling coil (*i.e.* ADP), but it is never possible due to inefficiency of the cooling coil. Therefore, the resulting condition of air coming out of the coil is shown by a point 2 on the straight line joining the points 1 and 4.

Actually, the cooling and dehumidification process follows the path as shown by a dotted curve in Fig. 10.14, but for calculation of psychrometric properties, only end points are important. Thus the cooling and dehumidification process shown by a line 1-2 may be assumed to have followed a path 1-A (*i.e.* dehumidification) and A-2 (*i.e.* cooling) as shown in Fig. 10.14. We see that the total heat removed from the air during the cooling and dehumidification process is

$$q = h_1 - h_2 = (h_1 - h_A) + (h_A - h_2) = LH + SH$$

where $\quad LH = h_1 - h_A =$ Latent heat removed due to condensation of vapour of the reduced moisture content $(W_1 - W_2)$, and

$\quad SH = h_A - h_2 =$ Sensible heat removed.

We know that sensible heat factor,

$$SHF = \frac{\text{Sensible heat}}{\text{Total heat}} = \frac{SH}{LH + SH} = \frac{h_A - h_2}{h_1 - h_2}$$

5. *Heating and Humidification.* This process is generally used in winter air conditioning to warm and humidify the air. It is the reverse process of cooling and dehumidification. The process of heating and humidification is shown by line 1-2 on the psychrometric chart, as shown in Fig. 10.15. The air enters at condition 1 and leaves at condition 2. In this process, the dry bulb temperature as well as specific humidity of air increases. The final relative humidity of air can be lower or higher than that of the entering air.

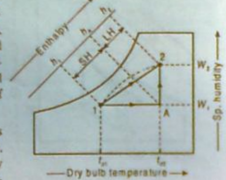


Fig. 10.15

Actually, the heating and humidification process follows the path as shown by a dotted curve in Fig. 10.15, but for the calculation of psychrometric properties, only the end points are important. Thus, the heating and humidification process shown by line 1-2 on the psychrometric chart may be assumed to have followed the path 1-A (*i.e.* heating) and A-2 (*i.e.* humidification). We know that sensible heat factor,

$$SHF = \frac{SH}{SH + LH} = \frac{h_A - h_1}{h_2 - h_1}$$

6. *Heating and Dehumidification (Adiabatic chemical Dehumidification).* This process is mainly used in industrial air conditioning and can be used for some comfort air conditioning installations requiring either a low relative humidity or low dew point temperature in the room.

In this process, the air is passed over chemicals which have an affinity for moisture. As the air comes in contact with these chemicals, the moisture gets condensed out of the air and gives up its latent heat. Due to the condensation, the specific humidity decreases and the heat of condensation supplies sensible heat for heating the air and thus increasing its dry bulb temperature. The process, which is the reverse of adiabatic saturation process, is shown by the line 1-2 on the psychrometric chart as shown in Fig. 10.16. The path followed during the process is along the constant wet bulb temperature line or constant enthalpy line.

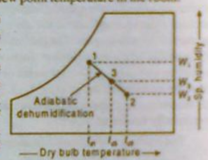


Fig. 10.16

The effectiveness or efficiency of the dehumidifier is given as

$$\eta_H = \frac{\text{Actual increase in DBT}}{\text{Ideal increase in DBT}} = \frac{t_{d3} - t_{d1}}{t_{d2} - t_{d1}}$$

OBJECTIVE TYPE QUESTIONS

1. The heat transfer takes place according to
   (*a*) Zeroth law of thermodynamics (*b*) First law of thermodynamics
   (*c*) Second law of thermodynamics (*d*) Kirchhoff's law
2. Conduction is a process of heat transfer
   (*a*) from one particle of the body to another without the actual motion of the particles
   (*b*) from one particle of the body to another by the actual motion of the heated particles
   (*c*) from a hot body to a cold body, in a straight line, without affecting the intervening medium
   (*d*) none of the above

3. Conduction is the process of heat transfer from one particle of the body to another by the actual motion of the heated particles.
   (*a*) True (*b*) False
4. Radiation is the process of heat transfer in which heat flows from a ...., in a straight line, without affecting the intervening medium.
   (*a*) cold body to hot body (*b*) hot body to cold body
   (*c*) smaller body to larger body (*d*) larger body to smaller body
5. The process of heat transfer from one particle of the body to another by the actual motion of the heated particles, is called
   (*a*) conduction (*b*) convection (*c*) radiation
6. The process of heat transfer from a hot body to a cold body, in a straight line, without affecting the intervening medium, is called radiation.
   (*a*) True (*b*) False
7. The process of heat transfer from one particle of the body to another is called conduction, when the particles of the body
   (*a*) move actually (*b*) do not move actually
   (*c*) affect the intervening medium (*d*) does not affect the intervening medium
8. In case of solids, the heat transfer takes place according to radiation.
   (*a*) Correct (*b*) Incorrect
9. In case of liquids and gases, the heat transfer takes place according to
   (*a*) conduction (*b*) convection (*c*) radiation (*d*) none of these
10. The heat of sun reaches to us according to
    (*a*) conduction (*b*) convection (*c*) radiation (*d*) none of these
11. The transfer of heat by molecular collision is known as
    (*a*) conduction (*b*) convection (*c*) radiation (*d*) none of these
12. The transfer of heat by molecular collision is smallest in
    (*a*) solids (*b*) liquids (*c*) gases (*d*) none of these
13. The heat is transferred by conduction, convection and radiation in
    (*a*) melting of ice (*b*) boiler furnaces
    (*c*) condensation of steam in condenser (*d*) none of these
14. The space between the two walls of a thermos flask is evacuated because vacuum is a .... conductor of heat.
    (*a*) good (*b*) bad
15. The heat transfer from a hot body to a cold body is directly proportional to the surface area and difference of temperatures between the two bodies. This statement is called
    (*a*) First law of thermodynamics (*b*) Newton's law of cooling
    (*c*) Newton's law of heating (*d*) Stefan's law
16. The transfer of heat from one body to another takes place only when there is a temperature difference between the bodies.
    (*a*) Yes (*b*) No

184. (b)	185. (a)	186. (d)	187. (a)	188. (b)	189. (c)
190. (d)	191. (a)	192. (d)	193. (b)	194. (a)	195. (b)
196. (b)	197. (d)	198. (a)	199. (c)	200. (d)	201. (d)
202. (a)	203. (c)	204. (b)	205. (c)	206. (b)	207. (a)
208. (d)	209. (c)	210. (c)	211. (c)	212. (b)	213. (d)
214. (a)	215. (d)	216. (a)	217. (c)	218. (a)	219. (d)
220. (b)	221. (b)	222. (a)	223. (a)	224. (b)	225. (d)
226. (a)	227. (c)	228. (a)	229. (d)	230. (b)	231. (c)
232. (b)	233. (a)	234. (d)	235. (b)	236. (a)	237. (b)
238. (b)	239. (a)	240. (a)	241. (a), (b)	242. (a)	243. (d)
244. (b)	245. (a)	246. (b)	247. (c)	248. (b)	249. (c)
250. (d)	251. (d)	252. (a), (b)	253. (d)	254. (d)	255. (a)
256. (a)	257. (b)	258. (c)	259. (d)	260. (c)	261. (d)
262. (a)	263. (b)	264. (c)	265. (b)	266. (c)	267. (a)
268. (b)	269. (b)	270. (c)	271. (b)	272. (a)	273. (d)
274. (c)	275. (a)	276. (c)	277. (d)	278. (b)	279. (c)
280. (a)	281. (c)	282. (d)	283. (a)	284. (a)	285. (c)
286. (b)	287. (d)	288. (a)	289. (c)	290. (d)	291. (b)
292. (b)	293. (a)	294. (d)	295. (a)	296. (d)	297. (c)
298. (b)	299. (a)	300. (b)	301. (c)	302. (b)	303. (a)
304. (a)	305. (b)	306. (b)	307. (c)	308. (d)	309. (b)
310. (b)	311. (a)	312. (b)	313. (b)	314. (b)	315. (d)
316. (c)	317. (a)	318. (b)	319. (a)	320. (b)	321. (d)
322. (a)	323. (b)	324. (c)	325. (a)	326. (d)	327. (a)
328. (a)	329. (a)	330. (a)	331. (a)	332. (a)	333. (b)
334. (b)	335. (a)	336. (d)	337. (a)	338. (a)	339. (b)
340. (b)	341. (b)	342. (b), (c)	343. (b)	344. (b)	345. (c)
346. (a)	347. (a)	348. (c)	349. (a)	350. (c)	351. (b)
352. (b)	353. (a)	354. (d)	355. (a)	356. (a)	357. (a)
358. (b)	359. (b)	360. (b)	361. (b)	362. (a)	363. (c)
364. (c)	365. (c)	366. (b)	367. (a)	368. (b)	369. (d)
370. (c)	371. (c)	372. (b)	373. (b)	374. (b)	375. (a)
376. (c)	377. (c)	378. (d)	379. (d)	380. (d)	381. (b)
382. (c)	383. (a)	384. (c)	385. (c)	386. (b)	387. (c)
388. (b)	389. (b)	390. (d)	391. (d)	392. (c)	393. (a)
394. (c)	395. (c)	396. (b)	397. (d)	398. (a)	399. (b)
400. (c)					

11

Theory of Machines

11.1 Introduction

The Theory of Machines may be defined as that branch of Engineering science, which deals with the study of relative motion between the various parts of a machine and the forces which act on them. Each part of a machine which moves relative to some other part, is known as a *kinematic link* (or simply *link*) or an *element*.

A link or element need not to be a rigid body, but it must be a resistant body. A body is said to be a resistant body if it is capable of transmitting the required forces with negligible deformation.

11.2 Kinematic Pair

The two links or elements of a machine, when in contact with each other, are said to form a pair. If the relative motion between them is completely or successfully constrained (*i.e.* in a definite direction), the pair is known as *kinematic pair*.

11.3 Types of Constrained Motions

Following are the three types of constrained motions :

1. *Completely constrained motion.* When the motion between a pair is limited to a definite direction irrespective of the direction of force applied, then the motion is said to be a completely constrained motion. For example, the piston and cylinder (in a steam engine) form a pair and the motion of the piston is limited to a definite direction (*i.e.* it will only reciprocate) relative to the cylinder irrespective of the direction of motion of the crank. The motion of a square bar in a square hole, and the motion of a shaft with collars at each end in a circular hole, are also examples of completely constrained motion.

2. *Incompletely constrained motion.* When the motion between a pair can take place in more than one direction, then the motion is called an incompletely constrained motion. A circular bar or shaft in a circular hole, is an example of an incompletely constrained motion as it may either rotate or slide in a hole. These both motions have no relationship with the other.

3. *Successfully constrained motion.* When the motion between the elements, forming a pair, is such that the constrained motion is not completed by itself, but by some other means, then the motion is said to be successfully constrained motion. The motion of an I.C. engine valve (these are kept on their seat by a spring) and the piston reciprocating inside an engine cylinder are the examples of successfully constrained motion.

11.4 Classification of Kinematic Pairs

The kinematic pairs may be classified according to the following considerations :

1. *According to the type of relative motion between the elements.* The kinematic pairs according to the type of relative motion between the elements are as follows:

(a) *Sliding pair.* When the two elements of a pair are connected in such a way that one can only slide relative to the other, the pair is known as a sliding pair. The piston and cylinder, cross-head and guides of a reciprocating steam engine, ram and its guides in shaper, tail stock on the lathe bed etc. are the examples of a sliding pair. A little consideration will show, that a sliding pair has a completely constrained motion.

(b) *Turning pair*. When the two elements of a pair are connected in such a wav that one can only turn or revolve about a fixed axis of another link, the pair is known as turning pair. A shaft with collars at both ends fitted into a circular hole, the crankshaft in a journal bearing in an engine, lathe spindle supr orted in head stock, cycle wheels turning over their axles etc. are the examples of a turning pair. A turning pair also has a completely constrained motion.

(c) *Rolling pair*. When the two elements of a pair are connected in such a way that one rolls over another fixed link, the pair is known as rolling pair. Ball and roller bearings are examples of rolling pair.

(d) *Screw pair*. When the two elements of a pair are connected in such a way that one element can turn about the other by screw threads, the pair is known as screw pair. The lead screw of a lathe with nut, and bolt with a nut are examples of a screw pair.

(e) *Spherical pair*. When the two elements of a pair are connected in such a way that one element (with spherical shape) turns or swivels about the other fixed element, the pair formed is called a spherical pair. The ball and socket joint, attachment of a car mirror, pen stand etc., are the examples of a spherical pair.

2. *According to the type of contact between the elements*. The kinematic pairs according to the type of contact between the elements are as follows:

(a) *Lower pair*. When the two elements of a pair have a surface contact when relative motion takes place and the surface of one element slides over the surface of the other, the pair formed is known as lower pair. It will be seen that sliding pairs, turning pairs and screw pairs form lower pairs.

(b) *Higher pair*. When the two elements of a pair have a line or point contact when relative motion takes place and the motion between the two elements is partly turning and partly sliding, then the pair is known as higher pair. A pair of friction discs, toothed gearing, belt and rope drives, ball and roller bearings and cam and follower are the examples of higher pairs.

3. *According to the type of closure*. The kinematic pairs according to the type of closure between the elements are as follows:

(a) *Self closed pair*. When the two elements of a pair are connected together mechanically in such a way that only required kind of relative motion occurs, it is then known as self closed pair. The lower pairs are self closed pair.

(b) *Force-closed pair*. When the two elements of a pair are not connected mechanically but are kept in contact by the action of external forces, the pair is said to be a force-closed pair. The cam and follower is an example of force closed pair, as it is kept in contact by the forces exerted by spring and gravity.

11.5 Kinematic Chain

A kinematic chain may be defined as a combination of kinematic pairs, joined in such a way that each link forms a part of two pairs and the relative motion between the links or elements is completely or successfully constrained. For example, the crankshaft of an engine forms a kinematic pair with the bearings which are fixed in a pair, the connecting rod with the crank forms a second kinematic pair, the piston with the connecting rod forms a third pair and the piston with the cylinder forms a fourth pair. The total combination of these links is a kinematic chain.

If each link is assumed to form two pairs with two adjacent links, then the relation between the number of pairs (p) forming a kinematic chain and the number of links (l) may be expressed in the form of an equation :

$$l = 2p - 4 \quad \text{...}(i)$$

Since in a kinematic chain each link forms a part of two pairs, therefore there will be as many links as the number of pairs.

Another relation between the number of links (l) and the number of joints (j) which constitute a kinematic chain is given by the expression :

$$j = \frac{3}{2}l - 2 \quad \text{...}(ii)$$

In order to determine the nature of chain *i.e.* whether the chain is a locked chain (structure) or kinematic chain or unconstrained chain, the following relation between the number of links and the number of binary joints, as given by A.W. Klein may be used:

$$j + \frac{h}{2} = \frac{3}{2}l - 2 \quad \text{...}(iii)$$

where j = Number of binary joints, h = Number of higher pairs, and l = Number of links.

When in equations (*ii*) or (*iii*), L.H.S. > R. H. S., then the chain is called a *locked chain* and forms a frame or structure which is used in bridges and trusses.

When L.H.S. = R. H. S., then the chain is a *kinematic chain* and when L. H. S. < R. H. S., then the chain is called *unconstrained chain*.

11.6 Mechanism and Inversion

When one of the links of a kinematic chain is fixed, the chain is known as *mechanism*. It may be used for transmitting or transforming motion *e.g.* engine indicators, typewriter etc.

A mechanism with four links is known as *simple mechanism*, and the mechanism with more than four links is known as *compound mechanism*. When a mechanism is required to transmit power or to do some particular type of work, it then becomes a *machine*. In such cases, the various links or elements have to be designed to withstand the forces (both static and kinetic) safely.

It may be noted that we can obtain as many mechanisms as the number of links in kinematic chain by fixing, in turn, different links in a kinematic chain. This method of obtaining different mechanisms by fixing different links in a kinematic chain, is known as *inversion* of the mechanism.

11.7 Types of Kinematic Chains and their Inversions

The most important kinematic chains are those which consist of four lower pairs, each pair being a sliding pair or a turning pair. The following three types of kinematic chains with four lower pairs are important:

1. *Four bar chain or Quadric cycle chain*. It consists of four links, each of them forms a turning pair. The inversions of four bar chain are as follows:

(a) Beam engine (Crank and lever mechanism).

(b) Coupling rod of a locomotive (Double crank mechanism).

(c) Watt's indicator mechanism (Double lever mechanism).

2. *Single slider crank chain*. It is a modification of the four bar chain. It consists of one sliding pair and three turning pairs. It is, usually, found is reciprocating steam engine mechanism. This type of mechanism converts rotary motion into reciprocating motion. The inversions of a single slider crank chain are found in the following mechanisms:

(*a*) Pendulum pump or Bull engine.

(*b*) Oscillating cylinder engine.

(*c*) Rotary internal combustion engine or Gnome engine.

(*d*) Crank and slotted lever quick return motion mechanism.

(*e*) Whitworth quick return motion mechanism.

3. *Double slider crank chain.* It consists of two sliding pairs and two turning pairs. The inversions of a double slider crank chain are as follows:

(*a*) Elliptical trammels.

(*b*) Scotch yoke mechanism.

(*c*) Oldham's coupling.

11.8 Simple Harmonic Motion

A body is said to move with simple harmonic motion, if it satisfies the following two conditions:

(*a*) Its acceleration is always directed towards the centre, known as point of reference or mean position; and

(*b*) Its acceleration is proportional to the distance from that point.

It may be noted that

1. The velocity of a body moving with simple harmonic motion at any instant is given by

$$v = \omega\sqrt{r^2 - x^2}$$

where ω = Uniform angular velocity of the body is rad/s,

r = Radius of the circle along which the body moves, and

x = Displacement of the body from the mean position.

The velocity is *maximum* at the mean position (*i.e.* when $x = 0$).

2. The acceleration of a body moving with simple harmonic motion at any instant is given by

$$a = \omega^2 x$$

The acceleration is *zero* at the mean position and *maximum* when $x = r$.

3. The maximum displacement of a body from its mean position is called *amplitude*.

4. The time taken for one complete revolution of the particle is called *periodic time*. It is given by

$$t_p = 2\pi/\omega \text{ seconds} = 2\pi\sqrt{\frac{x}{a}} \text{ seconds}$$

5. The number of cycles per second is called *frequency*. It is the reciprocal of periodic time. It is given by

$$n = \frac{\omega}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{a}{x}} \text{ Hz}$$

6. The periodic time and frequency of oscillation of a simple pendulum depends only upon its length (L) and acceleration due to gravity (g). Mathematically, for a simple pendulum,

Periodic time, $t_p = 2\pi\sqrt{\frac{L}{g}}$

and frequency of oscillation, $n = \frac{1}{t_p} = \frac{1}{2\pi}\sqrt{\frac{g}{L}}$

7. When a rigid body is suspended vertically and it oscillates with a small amplitude under the action of the force of gravity, the body is known as *compound pendulum*, as shown in Fig. 11.1. The periodic time for a compound pendulum is given by

$$t_p = 2\pi\sqrt{\frac{k_G^2 + h^2}{g.h}}$$

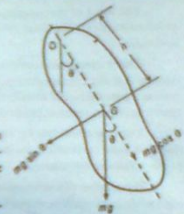


Fig. 11.1

and frequency of oscillation,

$$n = \frac{1}{t_p} = \frac{1}{2\pi}\sqrt{\frac{g.h}{k_G^2 + h^2}}$$

where k_G = Radius of gyration about an axis through the centre of gravity G and perpendicular to the plane of motion, and

h = Distance of point of suspension O from the centre of gravity G of the body.

8. The minimum periodic time of a compound pendulum is given by

$$t_p = 2\pi\sqrt{\frac{2k_G}{g}}$$

9. The equivalent length of a simple pendulum, which gives the same frequency as compound pendulum is

$$L = \frac{k_G^2 + h^2}{h}$$

10. The centre of percussion is below the centre of gravity and at a distance of k_G^2/h.

11. The distance between the centre of suspension and centre of percussion is equal to the equivalent length of a simple pendulum.

12. When one end of a closely-coiled helical spring is fixed and the other end carries a load W which moves with simple harmonic motion, then its periodic time,

$$t_p = 2\pi\sqrt{\frac{\delta}{g}}$$

and frequency, $n = \frac{1}{2\pi}\sqrt{\frac{g}{\delta}}$

13. The periodic time of a trifilar suspension or torsional pendulum is given by

$$t_p = \frac{2\pi k_G}{r}\sqrt{\frac{l}{g}}$$

and frequency, $n = \frac{1}{t_p} = \frac{r}{2\pi k_G}\sqrt{\frac{g}{l}}$

11.9 Instantaneous Centre

The instantaneous centre of a moving body may be defined as that centre which goes on changing from one instant to another. The locus of all such instantaneous centres is known as centrode. A line drawn through an instantaneous centre and perpendicular to the plane of motion is called *instantaneous axis*. The locus of this axis is known as *axode*.

The locus of the instantaneous centre in space during a definite motion of the body is called *space centrode* and the locus of the instantaneous centre relative to the body itself is called the *body centrode*.

The instantaneous centre method of analysing the motion is a mechanism is based upon the concept that any displacement of a body (or a rigid link) having motion in one plane, can be considered as a pure rotational motion of a rigid link as a whole about some centre known as instantaneous centre or virtual centre of rotation.

It may be noted that the velocities of the points on a rigid link is inversely proportional to the distances from the points to the instantaneous centre and is perpendicular to the line joining the point to the instantaneous centre.

The number of instantaneous centres in a constrained kinematic chain is equal to the number of possible combinations of two links. If n are the number of links, then the number of instantaneous centres are

$$N = \frac{n(n-1)}{2}$$

The following properties of the instantaneous centre are important:

1. A rigid link rotates instantaneously relative to another link at the instantaneous centre for the configuration of the mechanism considered.

2. The two rigid links have no linear velocity relative to each other at the instantaneous centre. At this point (*i.e.* instantaneous centre), the two rigid links have the same linear velocity relative to the third rigid link. In other words, the velocity of the instantaneous centre relative to any third rigid link will be same whether the instantaneous centre is regarded as a point on the first rigid link or on the second rigid link.

In a mechanism, the instantaneous centres may be of the following three types:

(*a*) *Fixed instantaneous centres.* The instantaneous centres, which remain in the same place for all configurations of the mechanism, are called fixed instantaneous centres.

(*b*) *Permanent instantaneous centres.* The instantaneous centres which moves as the mechanism moves but the joints are of permanent nature, are called permanent instantaneous centres.

(*c*) *Neither fixed nor permanent instantaneous centres.* The instantaneous centres which vary with the configuration of the mechanism, are called neither fixed nor permanent instantaneous centres.

The following rules may be used in locating the instantaneous centres in a mechanism:

1. When the two links are connected by a pin joint (or pivot joint), the instantaneous centre lies on the centre of the pin. Such a instantaneous centre is of permanent nature, but if one of the links is fixed, the instantaneous centre will be of fixed type.

2. When the two links have a pure rolling contact, the instantaneous centre lies on their point of contact.

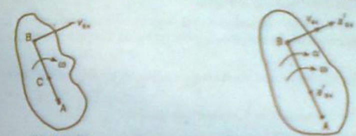
3. When the slider moves on fixed link having straight surface, the instantaneous centre lies at infinity and each point on the slider have the same velocity.

4. When the slider moves on fixed link having curved surface, the instantaneous centre lies on the centre of curvature of the curvilinear path in the configuration at that instant.

5. When the slider moves on fixed link having constant radius of curvature, the instantaneous centre lies at the centre of curvature *i.e.* the centre of the circle, for all configuration of the links.

11.10 Velocity and Acceleration in Mechanisms

The velocity of any point on a link with respect to another point on the same link is always perpendicular to the line joining these points on the configuration (or space) diagram.



(a) Velocity (b) Acceleration

Fig. 11.2

Consider two points A and B on a rigid link AB, as shown in Fig. 11.2 (*a*). Let one of the extremities (B) of the link move relative to A, in a clockwise direction. The relative velocity of B with respect to A (*i.e.* v_{BA}) is perpendicular to the line AB.

Again, consider two points A and B on a rigid link, as shown in Fig. 10.2 (*b*). Let the point B moves with respect to A, with an angular velocity of ω rad / s and let α rad/s^2 be the angular acceleration of the link AB. We know that the acceleration of a particle whose velocity changes both in magnitude and direction, has two components, *i.e.* radial or centripetal component and tangential component. These two components are perpendicular to each other.

The radial or centripetal component of acceleration of B with respect to A, is given by

$$a^r_{BA} = \omega^2 \times \text{Length of link } AB = \omega^2 \times AB = v^2_{BA} / AB \qquad ...(\because \omega = v_{BA} / AB)$$

This radial component of acceleration acts perpendicular to the velocity v_{BA}. In other words, it acts parallel to the link AB.

The tangential component of acceleration of B with respect to A, is given by

$$a^t_{BA} = \alpha \times AB$$

This tangential component of acceleration acts parallel to the velocity v_{BA}. In other words, it acts perpendicular to the link AB.

The angular acceleration of the link AB is given by

$$\alpha_{AB} = a^t_{BA} / AB$$

11.11 Coriolis Component of Acceleration

When a point on one link is sliding along another rotating link such as in quick return motion mechanism, then the Coriolis component of acceleration must the taken into account. It is the tangential component of the acceleration of the slider with respect to the coincident point on the link. Consider that a slider B moves at a velocity v on a link OA revolving at ω rad / s, as shown in Fig. 11.3.

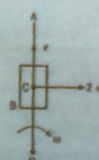


Fig. 11.3

The point C is the coincident point on the link OA. The Coriolis component of acceleration of B with respect to C is given by

$$a^c_{BC} = a^t_{BC} = 2\omega v$$

where v = Velocity of slider B with respect to coincident point C.

The Coriolis component of acceleration is always perpendicular to the link.

11.12 Mechanisms with Lower Pairs

We know that when the two elements of a pair have a surface contact and a relative motion takes place, the surface of one element slides over the other, the pair formed is known as lower pair. The mechanisms with lower pairs are as follows:

(*a*) *Pantograph*. It is an instrument used to reproduce to an enlarged or a reduced scale and as exactly as possible the path described by a given point. It consists of bars connected by turning pairs.

(*b*) *Exact straight line motion mechanisms made up of turning pairs*. These mechanisms are as follows:

(*i*) Peaucellier mechanism, and (*ii*) Hart's mechanism

(*c*) *Exact straight line motion mechanisms consisting of one sliding pair*. The Scott Russell's mechanism is of this type. Since the friction and wear of a sliding pair is much more than those of turning pair, therefore this mechanism is not of much practical value.

(*d*) *Approximate straight line motion mechanisms*. These mechanisms are as follows :

(*i*) Watt's mechanism; (*ii*) Modified Scott-Russel mechanism, (*iii*) Grasshopper mechanism; (*iv*) Tchebicheff's mechanism; and (*v*) Robert's mechanism.

11.13 Steering Gear Mechanism

The steering gear mechanism is used for changing the direction of two or more of the wheel axles with reference to the chassis, so as to move the automobile in any desired path. Usually the two back wheels have a common axis, which is fixed in direction with reference to the chassis and the steering is done by means of the front wheels.

The condition for correct steering is that all the four wheels must turn about the same instantaneous centre. The fundamental equation for correct steering is

$$\cot\phi - \cot\theta = c/b$$

where ϕ and θ = Angle through which the axis of the outer wheel and inner wheel turns respectively,

c = Distance between the pivots of the front axles, and

b = Wheel base.

In case of Davis steering gear, the condition for correct steering is

$$\tan\alpha = c/2b$$

where α = Angle of inclination of the links to the vertical.

The Ackerman steering gear mechanism is much simpler than Davis gear. The difference between the Ackerman and Davis steering gears are :

1. The whole mechanism of the Ackerman steering gear is on the back of the front wheels; whereas in Davis steering gear, it is in front of the wheels.

2. The Ackerman steering gear consists of turning pairs, whereas Davis steering gear consists of sliding members.

11.14 Universal or Hooke's Joint

A Hooke's joint is used to connect two shafts, which are intersecting at a small angle (say α). The ratio of velocities of the shafts connected by a Hooke's joint is given by

$$\frac{N}{N_1} = \frac{1-\cos^2\theta\sin^2\alpha}{\cos\alpha}$$

where N and N_1 = Speeds of the driving and driven shafts (in r.p.m.) respectively, and

θ = Angle through which the arms of the cross turn.

The speed of the driving and driven shafts will be equal, when

$$\tan\theta = \pm\sqrt{\cos\alpha}$$

11.15 Friction

A force acting in the opposite direction to the motion of the body is called *force of friction* or simply *friction*.

The friction experienced by a body, when at rest, is known as *static friction*.

The friction, experienced by a body, when in motion, is known as *dynamic* or *kinetic friction*. It is always less than static friction. The dynamic friction is of three types, *i.e.* sliding friction, rolling friction and pivot friction.

The maximum frictional force, which comes into play, when a body just begins to slide over the surface of the other body, is called *limiting friction*.

The laws of static friction are as follows:

1. The force of friction always acts in a direction, opposite to that in which the body tends to move.

2. The magnitude of the force of friction is exactly equal to the force, which tends the body to move.

3. The magnitude of the limiting friction (F) bears a constant ratio to the normal reaction (R_N) between the two surfaces. Mathematically,

$$F/R_N = \text{constant}$$

4. The force of friction is independent of the area of contact, between the two surfaces.

5. The force of friction depends upon the roughness of the surfaces.

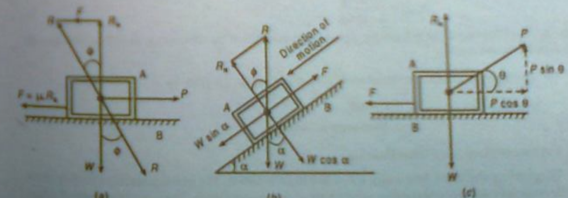


Fig. 11.4

The *coefficient of friction* is defined as the ratio of the limiting friction (F) to the normal reaction (R_N) between the two bodies. Mathematically, coefficient of friction,

$$\mu = F/R_N$$

The *limiting angle of friction* is defined as the angle which the resultant reaction R makes with the normal reaction R_N. From Fig. 11.4 (*a*).

$$\tan\phi = F/R_N = \mu.R_N/R_N = \mu$$

The *angle of repose* is defined as the angle of inclination of the plane (α) at which the body begins to move down the plane, as shown in Fig. 11.4 (*b*).

The minimum force required to slide a body of weight W on a rough horizontal plane, as shown in Fig. 11.4 (*c*), is given by

$$P = W\sin\theta$$

When a body of weight W is required to move up the rough inclined plane whose angle of inclination with the horizontal is α, then the effort required parallel to the plane to move the body is given by

$$P = W(\sin\alpha + \mu\cos\alpha)$$

where $\mu = \tan\phi$ = Coefficient of friction between the plane and the body.

The *screw jack*, used for raising or lowering the load, works on the same principle as that of an inclined plane. The load to be raised or lowered, is placed on the head of the square threaded rod which is rotated by the application of an effort at the end of the lever for lifting or lowering the load.

The effort required at the circumference of the screw to lift the load W is given by

$$P = W\tan(\alpha + \phi)$$

and the effort required at the circumference of the screw to lower the load W is given by

$$P = W\tan(\phi - \alpha)$$

where α = Helix angle, and ϕ = Angle of friction.

The efficiency of the screw jack is given by

$$\eta = \frac{\tan\alpha}{\tan(\alpha + \phi)}$$

The efficiency of the screw jack is maximum, when $\alpha = 45° - \phi/2$, and the maximum efficiency is given by

$$\eta_{max} = \frac{1 - \sin\phi}{1 + \sin\phi}$$

Notes: 1. The efficiency of the self locking screws is less than 50%. If the efficiency is more than 50%, then the screw is said to be overhauling.

2. In case of V-threads, the virtual coefficient of friction (μ_1) is given by

$$\mu_1 = \mu/\cos\beta$$

where β = Semi-angle of V-thread.

11.16 Friction of Pivot and Collar Bearing

The rotating shafts are frequently subjected to axial thrust. The bearing surfaces such as pivot and collar bearings are used to take this axial thrust of the rotating shaft. The propeller shafts of ships, the shafts of steam turbines, and vertical machine shafts are examples of shafts which carry an axial thrust.

The bearing surfaces placed at the end of a shaft to take the axial thrust are known as *pivots*. The pivot may have a flat surface or conical surface. When the cone is truncated, it is then known as truncated or trapezoidal pivot.

The collar may have flat bearing surface or conical bearing surface, but the flat surface is most commonly used. There may be a single collar or several collars along the length of a shaft in order to reduce the intensity of pressure.

A little consideration will show that in a new bearing, the contact between the shaft and bearing may be good over the whole surface. In other words, we can say that the pressure over the rubbing surfaces is uniformly distributed. But when the bearing becomes old, all parts of the rubbing surface will not move with the same velocity, because the velocity of rubbing surface increases with the distance from the axis of the bearing. This means that wear may be different at different radii and this causes to alter the distribution of pressure. Hence, in the study of friction of bearings, it is assumed that

1. The pressure is uniformly distributed throughout the bearing surface, and
2. The wear is uniform throughout the bearing surface.

Let us now study the expressions used in finding the frictional torque transmitted by different types of bearings :

(*a*) Frictional torque transmitted in a flat pivot bearing,

$$T = \frac{2}{3} \times \mu W R \quad \text{...(Considering uniform pressure)}$$

$$= \frac{1}{2} \times \mu W R \quad \text{...(Considering uniform wear)}$$

(*b*) Frictional torque transmitted in a conical pivot bearing,

$$T = \frac{2}{3} \times \mu W R \operatorname{cosec}\alpha \quad \text{...(Considering uniform pressure)}$$

$$= \frac{1}{2} \times \mu W R \operatorname{cosec}\alpha \quad \text{...(Considering uniform wear)}$$

where W = Load transmitted to the bearing,

R = Radius of the shaft, and

α = Semi-angle of the cone.

(*c*) Frictional torque transmitted in a trapezoidal or truncated conical pivot bearing,

$$T = \frac{2}{3} \times \mu W \operatorname{cosec}\alpha \left[\frac{(r_1)^3 - (r_2)^3}{(r_1)^2 - (r_2)^2}\right] \quad \text{...(Considering uniform pressure)}$$

$$= \frac{1}{2} \times \mu W \operatorname{cosec}\alpha\,(r_1 + r_2) = \mu W R \operatorname{cosec}\alpha \quad \text{...(Considering uniform wear)}$$

where r_1 and r_2 = External and internal radius of the conical bearing, and

R = Mean radius of the bearing = $\frac{r_1 + r_2}{2}$

(*d*) Frictional torque transmitted in a flat collar bearing,

$$T = \frac{2}{3} \times \mu W \left[\frac{(r_1)^3 - (r_2)^3}{(r_1)^2 - (r_2)^2}\right] \quad \text{...(Considering uniform pressure)}$$

$$= \frac{1}{2} \times \mu W (r_1 + r_2) \quad \text{...(Considering uniform wear)}$$

Notes: 1. The frictional torque transmitted by a disc or plate clutch is same as that of flat collar bearing.

2. In a disc or plate clutch, if there are n_1 number of discs on the driving shaft and n_2 are the number of discs on the driven shaft, then the number of pairs of contact surfaces will be $(n_1 + n_2 - 1)$.

3. The frictional torque transmitted by a cone clutch is same as that of truncated conical pivot bearing.

11.17 Flat Belt Drives

The power from one pulley to another may be transmitted either by open belt drive or crossed belt drive. The open belt drive is used with shafts arranged parallel and rotating in the same directions. The crossed belt drive is used with shafts arranged parallel and rotating in the opposite directions.

The velocity ratio of a belt drive is the ratio between the velocities of the driver and the follower or driven. Due to slip of belt, the velocity ratio of the belt drive decreases.

When two pulleys of radii r_1 and r_2 and at a distance x apart, are connected by means of an open belt drive, then the length of belt,

$$L = \pi (r_1 + r_2) + \frac{(r_1 - r_2)^2}{x} + 2x$$

When the pulleys are connected by means of a crossed belt drive, then length of belt,

$$L = \pi (r_1 + r_2) + \frac{(r_1 + r_2)^2}{x} + 2x$$

The creep in belt drive is due to uneven extensions and contractions of the belt when it passes from tight side to slack side.

Fig. 11.5 shows an open belt drive in which the driving pulley (or driver) A and the driven pulley (or follower) B rotate in the same clockwise directions. The power transmitted by the belt,

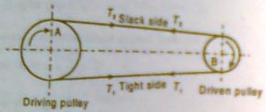


Fig. 11.5

$$P = (T_1 - T_2)\ v \text{ (in watts)}$$

where T_1 and T_2 = Tensions in the tight side and slack side of the belt respectively, in newtons, and

v = Velocity of the belt in m/s.

The ratio of driving tensions for flat belt drives is given by

$$\frac{T_1}{T_2} = e^{\mu\theta} \quad \text{or} \quad 2.3 \log\left(\frac{T_1}{T_2}\right) = \mu\theta$$

where μ = Coefficient of friction between the belt and the pulley, and

θ = Angle of contact in radians.

When the two pulleys of different diameters are connected by means of an open belt drive, then the angle of contact (θ) at the smaller pulley must be taken into consideration.

The centrifugal tension (T_c) is very small at lower speeds of belt (less than 10 m / s), but at higher belt speeds (more than 10 m / s), its effect is considerable and thus should be taken into account. Its value is given by

$$T_c = m.v^2$$

where m = Mass of the belt per unit length, and

v = Linear velocity of the belt.

The centrifugal tension on the belt has no effect on the power transmitted. The power transmitted by the belt is maximum, when the maximum tension in the belt (*i.e.* total tension in the tight side of the belt) is three times the centrifugal tension. The velocity of the belt for maximum power is

$$v = \sqrt{\frac{T}{3m}}, \text{ and } T = 3\,T_c$$

11.18 V – Belt Drive

A V-belt is mostly used in factories and workshops, where a great amount of power is to be transmitted from one pulley to another when the two pulleys are very near to each other.

The V-belts are made of fabric and cords moulded in rubber and covered with fabric and rubber. These belts are moulded to a trapezoidal shape and are made endless. These are particularly suitable for short drives *i.e.* when the shafts are at a short distance apart. The included angle for the V-belt is usually from 30° – 40°. In order to increase the power output, several V-belts may be operated side by side. In multiple V-belt drive, all the belts should stretch at the same rate so that the load is equally divided between them. When one of the set of belts break, the entire set should be replaced at the same time.

The ratio of driving tensions for the V-belt drive is

$$2.3 \log\left(\frac{T_1}{T_2}\right) = \mu.\theta \operatorname{cosec}\beta$$

where β = Semi-angle of the groove.

Note: In a rope drive, the ratio of driving tensions is same as that of V-belt drive.

11.19 Toothed Gearing

The gears are used to transmit power from one shaft to another when the shafts are at a small distance apart. It transmits exact velocity ratio. It has high efficiency, reliable service and compact layout. The gears may be classified as follows:

1. *According to the position of axes of the shafts.* The axes of the two shafts between which the motion is to be transmitted, may be

(*a*) Parallel, (*b*) Intersecting, and (*c*) Non-intersecting and non-parallel.

When two parallel and co-planer shafts are connected by gears having teeth parallel to the axis of the shaft, then these gears are called *spur gears* and the arrangement is known as *spur gearing*. Another name given to spur gearing is *helical gearing* in which teeth are inclined to the axis.

When two non-parallel or intersecting, but coplaner shafts are connected by gears, then these gears are called *bevel gears* and the arrangement is known as *bevel gearing*. The bevel gears, like spur gears, may also have their teeth inclined to the face of the bevel, in which case they are known as *helical bevel gears*.

When two non-intersecting and non-parallel *i.e.* non-coplanar shafts are connected by gears, then these gears are called *skew bevel gears* or *spiral gears* and the arrangement is known as *skew bevel gearing* or *spiral gearing*.

Notes: (*a*) When equal bevel gears (having equal teeth) connect two shafts whose axes are mutually perpendicular, then the bevel gears are known as *mitres*.

(*b*) The worm gearing is essentially a form of spiral gearing in which the shafts are usually at right angles.

2. *According to the peripheral velocity of the gears.* The gears, according to the peripheral velocity of the gears may be classified as :

(*a*) Low velocity, (*b*) Medium velocity, and (*c*) High velocity.

The gears having velocity less than 3 m/s are termed as *low velocity gears* and gears having velocity between 3 and 15 m/s are known as *medium velocity gears*. If the velocity of gears is more than 15 m/s, then these are called *high speed gears*.

3. *According to the type of gearing.* The gears, according to the type of gearing may be classified as :

(*a*) External gearing, (*b*) Internal gearing, and (*c*) Rake and pinion.

In *external gearing*, the gears of the two shafts mesh *externally* with each other. The larger of these two wheels in called *spur wheel* and the smaller wheel is called *pinion*. In an external gearing, the motion of the two wheels is always *unlike*.

In *internal gearing*, the gears of the two shafts mesh *internally* with each other. The larger of these two wheels is called *annular wheel* and the smaller wheel is called *pinion*. In an internal gearing, the motion of the two wheels is always like.

Sometimes, the gear of a shaft meshes externally and internally with the gears in a *straight line. Such type of gear is called *rack and pinion*. The straight line gear is called rack and the circular wheel is called pinion.

11.20 Terms Used in Gears

The following terms, which will be mostly used in gears, should be clearly understood at this stage. These terms are illustrated in Fig. 11.6.

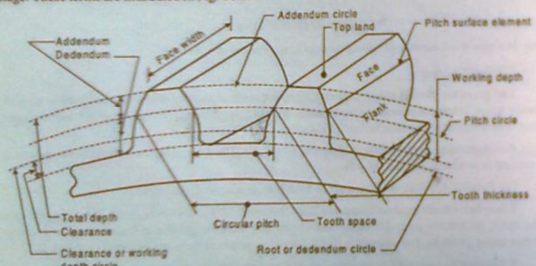


Fig. 11.6

1. *Pitch circle.* It is an imaginary circle which by pure rolling action, would give the same motion as the actual gear.

2. *Pitch circle diameter.* It is the diameter of the pitch circle. The size of the gear is usually specified by the pitch circle diameter. It is also called as *pitch diameter.*

3. *Pitch point.* It is a common point of contact between two pitch circles.

4. *Pitch surface.* It is the surface of the rolling discs which the meshing gears have replaced at the pitch circle.

5. *Pressure angle or angle of obliquity.* It is the angle between the common normal to two gear teeth at the point of contact and the common tangent at the pitch point. It is usually denoted by ϕ. The standard pressure angles are $14\frac{1^\circ}{2}$ and 20°.

* A straight line may also be defined as a wheel of infinite radius.

6. *Addendum.* It is the radial distance of a tooth from the pitch circle to the top of the tooth.

7. *Dedendum.* It is the radial distance of a tooth from the pitch circle to the bottom of the tooth.

8. *Addendum circle.* It is the circle drawn through the top of the teeth and is concentric with the pitch circle.

9. *Dedendum circle.* It is the circle drawn through the bottom of the teeth. It is also called root circle.

Note: Root circle diameter = Pitch circle diameter × cos ϕ, where ϕ is the pressure angle.

10. *Circular pitch.* It is the distance measured on the circumference of the pitch circle from a point of one tooth to the corresponding point on the next tooth. It is usually denoted by p_c. Mathematically, circular pitch.

$$p_c = \pi D / T$$

where D = Diameter of the pitch circle, and

T = Number of teeth on the wheel.

A little consideration will show that the two gears will mesh together correctly, if the two wheels have the same circular pitch.

Note: If D_1 and D_2 are the diameters of the two meshing gears having the teeth T_1 and T_2 respectively, then for them to mesh correctly,

$$p_c = \frac{\pi D_1}{T_1} = \frac{\pi D_2}{T_2} \quad \text{or} \quad \frac{D_1}{D_2} = \frac{T_1}{T_2}$$

11. *Diametral pitch.* It is the ratio of number of teeth to the pitch circle diameter in millimetres. It is denoted by p_d. Mathematically, diametral pitch,

$$p_d = \frac{T}{D} = \frac{\pi}{p_c} \qquad \ldots\left(\because p_c = \frac{\pi D}{T}\right)$$

where T = Number of teeth, and D = Pitch circle diameter.

12. *Module.* It is the ratio of the pitch circle diameter in millimetres to the number of teeth. It is usually denoted by m. Mathematically, module,

$$m = D / T$$

Note : The recommended series of modules in Indian Standard are 1, 1.25, 1.5, 2, 2.5, 3, 4, 5, 6, 8, 10, 12, 16, and 20. The modules 1.125, 1.375, 1.75, 2.25, 2.75, 3.5, 4.5, 5.5, 7, 9, 11, 14 and 18 are of second choice.

13. *Clearance.* It is the radial distance from the top of the tooth to the bottom of the tooth, in a meshing gear. A circle passing through the top of the meshing gear is known as *clearance circle.*

14. *Total depth.* It is the radial distance between he addendum and the dedendum of a gear. It is equal to the sum of the addendum and dedendum.

15. *Working depth.* It is the radial distance from the addendum circle to the clearance circle. It is equal to the sum of the addendum of the two meshing gears.

16. *Tooth thickness.* It is the width of the tooth measured along the pitch circle.

17. *Tooth space.* It is the width of space between the two adjacent teeth measured along the pitch circle.

18. *Backlash.* It is the difference between the tooth space and the tooth thickness, as measured along the pitch circle. Theoretically, the backlash should be zero, but in actual practice some backlash must be allowed to prevent jamming of the teeth due to tooth errors and thermal expansion.

19. *Face of tooth.* It is the surface of the gear tooth above the pitch surface.

20. *Flank of tooth.* It is the surface of the gear tooth below the pitch surface.

21. *Top land.* It is the surface of the top of the tooth.

22. *Face width.* It is the width of the gear tooth measured parallel to its axis.

23. *Profile.* It is the curve formed by the face and flank of the tooth.

24. *Fillet radius.* It is the radius that connects the root circle to the profile of the tooth.

25. *Path of contact.* It is the path traced by the point of contact of two teeth from the beginning to the end of engagement.

26. *Length of the path of contact.* It is the length of the common normal cut-off by the addendum circles of the wheel and pinion.

27. *Arc of contact.* It is the path traced by a point on the pitch circle from the beginning to the end of engagement of a given pair of teeth. The arc of contact consists of two parts, *i.e.*,

(*a*) *Arc of approach.* It is the portion of the path of contact from the beginning of the engagement to the pitch point.

(*b*) *Arc of recess.* It is the portion of the path of contact from the pitch point to the end of the engagement of a pair of teeth.

Note : The ratio of the length of arc of contact to the circular pitch is known as *contact ratio i.e.* number of pairs of teeth in contact.

11.21 Law of Gearing

According to the law of gearing, the common normal at the point of contact between a pair of teeth must always pass through the pitch point.

The following points in connection with the gears are worth noting:

(*a*) The velocity of sliding of teeth is the velocity of one tooth relative to its mating tooth along the common tangent at the point of contact.

(*b*) The velocity of sliding is directly proportional to the distance of the point of contact from the pitch point.

(*c*) The length of arc of contact

$$= \frac{\text{Length of path of contact}}{\cos\phi}$$

where ϕ = Pressure angle.

(*d*) Contact ratio or number of pairs of teeth in contact

$$= \frac{\text{Length of arc of contact}}{\text{Circular pitch}}$$

(*e*) The phenomenon when the tip of a tooth under cuts the root on its mating gear, is known interference.

(*f*) The interference may only be avoided, if the addendum circles of the two mating gears cut common tangent to the base circles between the points of tangency.

(*g*) The minimum number of teeth on the pinion in order to avoid interference for $14\frac{1°}{2}$ full depth involute are 32 and for 20° full depth involute teeth are 18.

(*h*) The maximum efficiency of spiral gears is given by

$$\eta_{max} = \frac{\cos(\theta+\phi)+1}{\cos(\theta-\phi)-1}$$

where θ = Shaft angle, and ϕ = Friction angle.

11.22 Gear Trains

Sometimes, two or more gears are made to mesh with each other to transmit power from one shaft to another. Such a combination is called *gear train*. The nature of the train used depends upon the velocity ratio required and the relative position of the axes of shafts.

Following are the different types of gear trains, depending upon the arrangement of gears:

1. Simple gear train, 2. Compound gear train, 3. Reverted gear train, and 4. Epicyclic gear train.

In a simple gear train, there is only one gear on each shaft. In a compound gear train, there are more than one gear on each shaft. In a reverted gear train, the axes of the first gear and the last gear are co-axial. In an epicyclic gear train, the axes of the shafts, over which the gears are mounted, may move relative to a fixed axis.

11.23 Gyroscopic Couple and Precessional Motion

The axis of precession is perpendicular to the plane in which the axis of spin is going to rotate.

The gyroscopic principle is used in an instrument or toy known as gyroscope. The gyroscopes are installed in ships in order to minimise the rolling and pitching effect of waves. They are also used in aeroplanes, monorail cars, gyro compasses etc.

The gyroscopic couple is usually applied through the bearings which support the shaft. The bearings will resist equal and opposite couple.

The effect of gyroscopic couple on an aeroplane and a naval ship are discussed as below:

(*a*) When the engine or propeller of an aeroplane rotates in the clockwise direction when seen from the rear or tail end and the aeroplane takes a turn to the left, then the effect of gyroscopic couple will be to raise the nose and dip the tail of the aeroplane.

Notes: 1. When the aeroplane takes a right turn under similar conditions as discussed above, the effect of the gyroscopic couple will be to dip the nose and raise the tail of the aeroplane.

2. When the engine or propeller rotates in anticlockwise direction when viewed from the rear or tail end and the aeroplane takes a left turn, then the effect of gyroscopic couple will be to dip the nose and raise the tail of the aeroplane.

3. When the aeroplane takes a right turn under similar conditions as mentioned in note 2 above, the effect of gyroscopic couple will be to raise the nose and dip the tail of the aeroplane.

4. When the engine or propeller rotates in clockwise direction when viewed from the front and the aeroplane takes a left turn, then the effect of gyroscopic couple will be to raise the tail and dip the nose of the aeroplane.

5. When the aeroplane takes a right turn under similar conditions as mentioned in note 4 above, the effect of gyroscopic couple will be to raise the nose and dip the tail of the aeroplane.

(*b*) In a naval ship, the fore end is known as *bow* and the rear end is called *stern* or *aft*. The left and right hand sides of the ship, when viewed from the stern, are called *port* and *star-board* respectively. We shall discuss the effect of gyroscopic couple on the naval ship in the following three cases:

(*i*) *Steering.* The steering is the turning of a complete ship in a curve towards left or right, while it moves forward. When the rotor of a ship rotates in the clockwise direction when viewed from the stern and the ship during steering takes a left turn, then the effect of gyroscopic couple will be to raise the bow and lower the stern.

Notes: 1. When the ship steers to the right under similar conditions as discussed above, the effect of the gyroscopic couple, will be to raise the stern and lower the bow.

2. When the rotor rotates in the anticlockwise direction, when viewed from the stern and the ship is steering to the left, then the effect of gyroscopic couple will be to lower the bow and raise the stern.

3. When the ship is steering to the right under similar conditions as discussed in note 2 above, then the effect of gyroscopic couple will be to raise the bow and lower the stern.

4. When the rotor rotates in the clockwise direction when viewed from the bow or fore end and the ship is steering to the left, then the effect of gyroscopic couple will be to raise the stern and lower the bow.

5. When the ship is steering to the right under similar conditions as discussed in note 4 above, then the effect of gyroscopic couple will be to raise the bow and lower the stern.

6. The effect of the gyroscopic couple on a boat propelled by a turbine taking left or right turn is similar as discussed above.

(*ii*) *Pitching*. The pitching is the movement of a complete ship up and down in a vertical plane about transverse axis.

When the pitching is upward, the effect of the gyroscopic couple will try to move the ship towards star-board. On the other hand, if the pitching is downward, the effect of the gyroscopic couple, is to turn the ship towards port side.

Notes: 1. The effect of the gyroscopic couple is always given on specific position of the axis of spin, *i.e.* whether it is pitching downwards or upwards.

2. The pitching of a ship produces forces on the bearings which act horizontally and perpendicular to the motion of the ship.

3. The maximum gyroscopic couple tends to shear the holding-down bolts.

(*iii*) *Rolling*. In case of rolling of a ship, the axis of precession (*i.e.* longitudinal axis) is always parallel to the axis of spin for all positions. Hence, there is no effect of the gyroscopic couple acting on the body of a ship.

11.24 Inertia forces in Reciprocating Parts

The inertia force is an imaginary force, which when acts upon a rigid body, brings it in an equilibrium position. It is numerically equal to the accelerating force in magnitude, but *opposite* in direction. The following relations are important with regard to forces in reciprocating parts :

(*a*) The displacement of the piston in a reciprocating steam engine when the crank has turned through an angle θ from the inner dead centre, is given by

$$x = r\left[(1-\cos\theta) + \frac{\sin^2\theta}{2n}\right]$$

where r = Radius of crank, and

n = Ratio of length of the connecting rod to the radius of crank.

(*b*) The velocity of the piston in a reciprocating steam engine is given by

$$v_p = \omega r\left(\sin\theta + \frac{\sin 2\theta}{2n}\right)$$

where ω = Angular velocity of the crank, and

θ = Angle turned by the crank from inner dead centre.

Note : When the crank is at inner dead centre, then $\theta = 0°$. Therefore, $v_p = 0$

(*c*) The acceleration of the piston in a reciprocating steam engine is given by

$$a_p = \omega^2 r\left[\cos\theta + \frac{\cos 2\theta}{n}\right]$$

Notes: 1. When the crank is at inner dead centre, then $\theta = 0°$.

$$\therefore \quad a_p = \omega^2 r\left(1 + \frac{1}{n}\right)$$

2. When the crank is at outer dead centre, then $\theta = 180°$.

$$\therefore \quad a_p = \omega^2 r\left(1 - \frac{1}{n}\right)$$

(*d*) The angular velocity of the connecting rod is given by

$$\omega_C = \frac{\omega\cos\theta}{(n^2 - \sin^2\theta)^{1/2}}$$

and the angular acceleration of the connecting rod,

$$\alpha_C = \frac{-\omega^2 \sin\theta(n^2 - 1)}{(n^2 - \sin^2\theta)^{3/2}}$$

11.25 Equivalent Dynamical System

In order to determine the motion of a rigid body, under the action of external forces, it is usually convenient to replace the rigid body by two masses placed at a fixed distance apart, in such a way that,

1. the sum of their masses is equal to the total mass of the body;
2. the centre of gravity of the two masses coincides with that of the body; and
3. the sum of mass moment of inertia of the masses about their centre of gravity is equal to the mass moment of inertia of the body.

When these three conditions are satisfied, then it is said to be an *equivalent dynamical system*. Consider a rigid body, having its centre of gravity at G, as shown in Fig. 11.7.

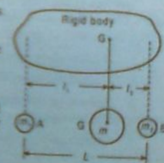


Fig. 11.7

The essential condition of placing the two masses, so that the system becomes dynamical equivalent, is

$$l_1 l_2 = (k_G)^2$$

where l_1 and l_2 = Distance of two masses m_1 and m_2 from the centre of gravity G of the body, and

k_G = Radius of gyration of the body about its centre of gravity.

Note: When the radius of gyration k_G is not known, then the position of the second mass may be obtained by considering the body as a compound pendulum. We have already discussed, that the length of the simple pendulum which gives the same frequency as the rigid body (*i.e.* compound pendulum) is

$$L = \frac{(k_G)^2 + h^2}{h} = \frac{(k_G)^2 + (l_1)^2}{l_1} \qquad \text{...(Replacing } h \text{ by } l_1)$$

We also know that, $l_1 l_2 = (k_G)^2$

$$L = \frac{l_1 l_2 + (l_1)^2}{l_1} = l_2 + l_1$$

This means that the second mass is situated at the centre of oscillation or percussion of the body which is at a distance of $l_2 = (k_G)^2 / l_1$.

11.26 Turning Moment Diagrams and Flywheel

The turning moment diagram (also known as *crank-effort diagram*) is the graphical representation of the turning moment or crank effort for various positions of the crank. It is plotted on cartesian co-ordinates, in which the turning moment is taken as the ordinate and crank angle as abscissa.

A flywheel used in machines controls the speed variations caused by the fluctuation of the engine turning moment during each cycle of operation.

The difference between the maximum and minimum energies is known as *maximum fluctuation of energy* and the ratio of the maximum fluctuation of energy to the work done per cycle is called *coefficient of fluctuation of energy*.

The difference between the maximum and minimum speeds during a cycle is called the *maximum fluctuation of speed* and the ratio of the maximum fluctuation of speed to the mean speed is called the *coefficient of fluctuation of speed*.

The maximum fluctuation of energy (ΔE) in a flywheel is given by

$$\Delta E = I\omega(\omega_1 - \omega_2) = I\omega^2 C_S = 2EC_S$$

where I = Mass moment of inertia of the flywheel,

ω_1 and ω_2 = Maximum and minimum angular speeds,

ω = Mean angular speed $= \dfrac{\omega_1 + \omega_2}{2}$,

E = Mean kinetic energy of the flywheel $= \dfrac{1}{2} I\omega^2$

C_S = Coefficient of fluctuation of speed.

11.27 Steam Engine Valves and Reversing Gears

The valves are used to control the steam which drives the piston of a reciprocating steam engine. The valves have to perform the following four distinct operations on the steam used on one side (*i.e.* cover end) of the piston.

1. Admission or opening of inlet valve for admission of steam to cylinder.
2. Cut-off or closing of inlet valve in order to stop admission of steam prior to expansion.
3. Release or opening of exhaust valve to allow the expanded steam to escape from the cylinder to the atmosphere.
4. Compression or closing of exhaust valve for stopping the release of steam from the cylinder prior to compression.

The same operations, as discussed above, are performed on steam in the same order on the other side (or crank end) of the piston for each cycle or each revolution of the crank shaft. In other words, for a double acting piston, there are eight valve operations per cycle. All these eight operations may be performed by a D - slide valve, piston slide valve and Meyer's expansion valve.

11.28 D-slide Valve

The simplest type of the slide valve called the D-slide valve, is most commonly used to control the admission, cut-off, release and compression of steam in the cylinder of reciprocating steam engine. Since the steam is admitted from outside the steam chest, therefore, this valve is also known as *outside admission valve*. The following terms are important in relation to D-slide valve :

(*a*) *Steam lap or outside lap.* It is the distance by which the outer edge of the D-slide valve overlaps the steam port.

Note: In actual practice, the displacement of the D-slide valve is greater than the steam lap by a distance known as *lead* of the valve.

(*b*) *Exhaust lap or inside lap.* It is the distance by which the inner edge of the D-slide valve overlaps the steam port.

(*c*) *Valve travel.* It is the distance moved by the valve from one end to the other end.

Note: The eccentricity or throw of the eccentric is equal to half of the valve travel.

11.29 Piston Slide Valve

The piston slide valve consists of two rigidly connected pistons. Since the steam enters from the inside of the two pistons, therefore, the piston valve is also known as *inside admission valve*. The piston slide valve has the following advantages over the D-slide valve:

(*a*) The power absorbed in operating the piston valve is less than the D-slide valve.

(*b*) The wear of the piston valve is less than the wear of the D-slide valve.

11.30 Meyer's Expansion Valve

The Meyer's expansion valve consists of two valves known as main valve and expansion valve which are driven by separate eccentrics from the main crankshaft. The main valve is driven by an eccentric having an angle of advance of 25° to 30° and the expansion valve is driven by an eccentric having an angle of advance 80° to 90°. If the engine has to be reversible, the angle of advance must be 90° so that the cut-off takes place at the same fraction of the stroke for the same setting of the expansion valve whatever may be the direction of rotation of the crank.

Note: The virtual or equivalent eccentric for the Meyer's expansion valve is defined as an eccentric having such a length and angle of advance that will cause cut-off to take place at the same position, as is caused by the combined effect of main eccentric and expansion eccentric.

11.31 Governors

The function of a governor is to regulate the mean speed of an engine, when there are variations in the load *e.g.* when the load on an engine increases, its speed decreases, therefore it becomes necessary to increase the supply of working fluid. On the other hand, when the load on the engine decreases, its speed increases and thus less working fluid is required. The governor automatically, controls the supply of working fluid to the engine with the varying load conditions and keeps the mean speed within certain limits.

Note: The function of a flywheel in an engine is entirely different from that of a governor. It controls the speed variation caused by the fluctuations of the engine turning moment during each cycle of operation. It does not control the speed variations caused by a varying load. The varying demand for power is met by the governor regulating the supply of working fluid.

11.32 Terms Used in Governors

The following terms used in governors are important from the subject point of view :

1. *Height of a governor.* It is the vertical distance from the centre of the ball to a point where the axes of the arms (or arms produced) intersect on the spindle axis. It is usually denoted by *h*.

2. *Equilibrium speed.* It is the speed at which the governor balls, arms etc., are in complete equilibrium and the sleeve does not tend to move upwards or downwards.

3. *Mean equilibrium speed.* It is the speed at the mean position of the balls or the sleeve.

4. *Maximum and minimum equilibrium speeds.* The speeds at the maximum and minimum

radius of rotation of the balls, without tending to move either way are known as maximum and minimum equilibrium speeds respectively.

Note : There can be many equilibrium speeds between the mean and the maximum and the mean and the minimum equilibrium speeds.

5. *Sleeve lift.* It is the vertical distance which the sleeve travels due to change in equilibrium speed.

11.33 Types of Governors

Following are the various types of governors:

1. *Watt governor.* It is the simplest type of a centrifugal governor. If N is the speed of the arm and ball about the spindle axis, then the height of the governor (h) is given by

$$h = \frac{895}{N^2} \text{ metres}$$

From this expression, we see that the height of a governor is inversely proportional to N^2. This governor may only work satisfactorily at low speeds *i.e.* from 60 to 80 r.p.m.

2. *Porter governor.* It is a modification of a Watt governor, with a central load attached to the sleeve. When the sleeve moves upwards, the governor speed increases and when the sleeve moves downwards, the governor speed decreases.

The ratio of height of a Porter governor (when length of arms and links are equal) to the height of watt's governor is $\dfrac{m+M}{m}$, where m and M are the masses of the ball and sleeve respectively.

3. *Hartnell governor.* It is a spring controlled governor. In a Hartnell governor, the compression of the spring or lift of the sleeve (h) is given by

$$h = (r_2 - r_1)\frac{y}{x}$$

and stiffness of the spring, $$s = \frac{S_2 - S_1}{h}$$

where r_1 = Minimum radius of rotation,

r_2 = Maximum radius of rotation,

S_1 = Spring force exerted at the minimum radius of rotation,

S_2 = Spring force exerted at the maximum radius of rotation,

x = Length of the vertical or ball arm of the lever, and

y = Length of the horizontal or sleeve arm of the lever.

11.34 Sensitiveness of Governors

Consider two governors A and B running at the same speed. When this speed increases or decreases by a certain amount, the lift of the sleeve of governor A is greater than the lift of the sleeve of governor B. It is then said that the governor A is more sensitive than the governor B.

In general, the greater the lift of the sleeve corresponding to a given fractional change in speed, the greater is the sensitiveness of the governor. It may also be stated in another way that for a given life of the sleeve, the sensitiveness of the governor increases as the speed range decreases. The sensitiveness is defined as *the ratio of the difference between the maximum and minimum equilibrium speeds to the mean equilibrium speed.*

11.35 Stability of Governors

A governor is said to be *stable* when for every speed within the working range there is a definite configuration *i.e.*, there is only one radius of rotation of the governor balls at which the governor is in equilibrium. For a stable governor, if the equilibrium speed increases, the radius of governor balls must also increase.

Note : A governor is said to be unstable, if the radius of rotation decreases as the speed increases.

11.36 Isochronous Governors

A governor is said to be *isochronous* when the equilibrium speed is constant (*i.e.* range of speed is zero) for all radii of rotation of the balls within the working range, neglecting friction. The isochronism is the stage of infinite sensitivity.

11.37 Hunting

A governor is said to be *hunt* if the speed of the engine fluctuates continuously above and below the mean speed. This is caused by a too sensitive governor which changes the fuel supply by a large amount when a small change in the speed of rotation takes place.

11.38 Effort and Power of a Governor

The effort of a governor is the mean force exerted at the sleeve for a given percentage change of speed or lift of the sleeve.

The *power of a governor* is the workdone at the sleeve for a given percentage change of speed. It is the product of the mean value of the effort and the distance through which the sleeve moves. Mathematically,

$$\text{Power} = \text{Mean effort} \times \text{Lift of sleeve}$$

11.39 Brakes and Dynamometers

A brake is a device by means of which artificial frictional resistance is applied to a moving machine member, in order to retard or stop the motion of a machine. The following types of brakes are commonly used:

1. Shoe brake, 2. Band brake, 3. Band and block brake; and 4. Internal expanding brake.

A dynamometer is a brake but in addition it has a device to measure the frictional resistance. Knowing the frictional resistance, we may obtain the torque transmitted and hence power of the engine.

Following are the two types of dynamometers, used for measuring the brake power of an engine :

1. *Absorption dynamometers.* In the absorption dynamometers, the entire energy or power produced by the engine is absorbed by the friction resistances of the brake and is transformed into heat, during the process of measurement. The following are two types of absorption dynamometers :

(*a*) Prony brake dynamometer; and 2. Rope brake dynamometer.

2. *Transmission dynamometers.* In the transmission dynamometers, the energy is not wasted in friction but is used for doing work. The energy or power produced by the engine is transmitted through the dynamometer to some other machines where the power developed is suitably measured. The following are three types of transmission dynamometers:

(*a*) Epicyclic-train dynamometer; (*b*) Belt transmission dynamometer; and (*c*) Torsion dynamometer.

11.40 Cams

A *cam* is a rotating machine element which gives reciprocating or oscillating motion to another element known as *follower*. The cams are usually rotated at uniform speed by a shaft, but the follower motion is predetermined and will be according to the shape of the cam. The cams are widely used for operating the inlet and exhaust valves of internal combustion engines, automatic attachment of machineries, paper cutting machines, spinning and weaving textile machineries, feed mechanism of automatic lathes etc.

The followers are classified as follows:

(*a*) Knife edge follower; (*b*) Roller follower; (*c*) Flat faced or mushroom follower; (*d*) Spherical faced follower; (*f*) Oscillating or rotating follower; (*g*) Radial follower; and (*h*) Off-set follower.

The cams are classified as follows:

(*a*) *Radial or disc cam.* In this type of cam, the follower reciprocates or oscillates in a direction perpendicular to the cam axis.

(*b*) *Cylindrical cam.* In this type of cam, the follower reciprocates or oscillates in a direction parallel to the cam axis.

11.41 Terms Used in Radial Cams

Fig. 11.8 shows a radial cam with reciprocating roller follower. The following terms are important in order to draw the cam profile.

1. *Base circle.* It is the smallest circle that can be drawn to the cam profile.

2. *Trace point.* It is a reference point on the follower and is used to generate the *pitch curve*. In case of knife edge follower, the knife edge represents the trace point and the pitch curve corresponds to the cam profile. In a roller follower, the centre of the roller represents the trace point.

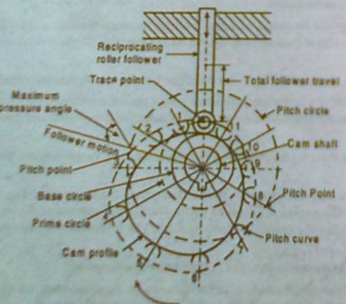


Fig. 11.8

3. *Pressure angle.* It is the angle between the direction of the follower motion and a normal to the pitch curve. This angle is very important in designing a cam profile. If the pressure angle is too large, a reciprocating follower will jam in its bearings.

4. *Pitch point.* It is a point on the pitch curve having the maximum pressure angle.

5. *Pitch circle.* It is a circle drawn from the centre of the cam through the pitch points.

6. *Pitch curve.* It is the curve generated by the trace point as the follower moves relative to the cam. For a knife edge follower, the pitch curve and the cam profile are same where as for a roller follower, they are separated by the radius of the roller.

7. *Prime circle.* It is the smallest circle that can be drawn from the centre of the cam and tangent to the pitch curve. For a knife edge and a flat face follower, the prime circle and the base circle are identical. For a roller follower, the prime circle is larger than the base circle by the radius of the roller.

8. *Lift or stroke.* It is the maximum travel of the follower from its lowest position to the topmost position.

11.42 Tangent Cam with Reciprocating Roller Follower

When the flanks of the cam are straight and tangential to the base circle and nose circle, then the cam is known as a *tangent cam*. These cams are usually symmetrical about the centre line of the cam shaft. Such type of cams are used for operating the inlet and exhaust valves of I.C. engines. The displacement, velocity and acceleration of the reciprocating roller follower when it has contact with the straight flanks, are as follows:

(*a*) Displacement $= (r_1 + r_2)(1 - \cos\theta)\sec\theta$

(*b*) Velocity $= \omega(r_1 + r_2)(\sin\theta\sec^2\theta)$

(*c*) Acceleration $= \omega^2(r_1 + r_2)(2 - \cos^2\theta)\sec^3\theta$

where
r_1 = Minimum radius of the cam,
r_2 = Radius of the roller follower,
θ = Angle turned by the cam, from the beginning of the follower displacement, and
ω = Angular velocity of the cam.

11.43 Circular Arc Cam with Flat-faced Follower

When the flanks of the cam connecting the base circle and nose are of convex circular arcs, then the cam is known as *circular arc cam*. The displacement, velocity and acceleration of the flat-faced follower when it has contact on the circular flank, are as follows:

(*a*) Displacement $= (R - r_1)(1 - \cos\theta)$

(*b*) Velocity $= \omega(R - r_1)\sin\theta$

(*c*) Acceleration $= \omega^2(R - r_1)\cos\theta$

where
R = Radius of circular flank,
r_1 = Minimum radius of the cam,
θ = Angle turned through by the cam, and
ω = Angular velocity of the cam.

11.44 Balancing of Rotating and Reciprocating Masses

The high speed of engines and other machines is a common phenomenon now-a-days. It is, therefore, very essential that all the rotating and reciprocating parts should be completely balanced as far as possible. If these parts are not properly balanced, the dynamic forces are set up. These forces not only increase the load on bearings and stresses in the various members, but also produce unpleasant and even dangerous vibrations.

First of all, let us discuss the balancing of unbalanced forces caused by rotating masses.

(*a*) *Balancing of rotating masses.* We know that whenever a certain mass is attached to a rotating shaft, it exerts some centrifugal force, whose effect is to bend the shaft and to produce vibrations in it. In order to prevent the effect of centrifugal force, another mass is attached to the opposite side of the shaft, at such a position so as to balance the effect of the centrifugal force of the first mass. This is done in such a way, that the centrifugal force of both the masses are made to be equal and opposite. The process of providing the second mass in order to counteract the effect of the centrifugal force of the first mass, is called *balancing of rotating masses.*

Consider a disturbing mass m_1, attached to a rotating shaft at a radius of rotation r_1. In order to balance the effect of centrifugal force produced by this mass, a second mass m_2 (called balancing mass) must be attached in the same plane at a *radius of rotation r_2 such that the centrifugal force of both the masses is equal. In other words,

$$m_1\omega^2 r_1 = m_2\,\omega^2 r_2 \quad \text{or} \quad m_1 r_1 = m_2 r_2$$

where ω = Angular speed of the shaft.

This arrangement for balancing gives rise to a couple which tends to rock the shaft in its bearing. Therefore, in order to put the system in complete balance, the following two conditions must be satisfied.

1. The net dynamic force acting on the shaft is equal to zero. This is the condition for *static balancing.*

2. The net couple due to dynamic forces acting on the shaft is equal to zero.

The conditions (1) and (2) together give *dynamic balancing.*

When several masses revolve in different planes, the following two conditions must be satisfied in order to have a complete balance:

1. The resultant force must be zero, and 2. The resultant couple must be zero.

(*b*) *Balancing of reciprocating masses.* There are various forces acting on the reciprocating parts of an engine. The resultant of all the forces acting on the body of the engine due to inertia forces only is known as *unbalanced force* or *shaking force.* Thus if the resultant of all the forces due to inertia effects is zero, then there will be no unbalanced force, but even then an unbalanced couple or shaking couple will be present.

The purpose of balancing the reciprocating masses is to eliminate the shaking force and a shaking couple. In most of the mechanisms, we can reduce the shaking force and a shaking couple by adding appropriate balancing mass, but it is usually not practical to eliminate them completely. In other words, the reciprocating masses are only partially balanced.

We know that the inertia force due to reciprocating parts or force required to accelerate the reciprocating parts,

$$F_I = F_R = \text{Mass} \times \text{Acceleration} = m\omega^2 r\left(\cos\theta + \frac{\cos 2\theta}{n}\right)$$

The horizontal component of the force exerted on the crank shaft bearing is equal and opposite to inertia force (F_I). This force is an unbalanced one and is denoted by F_U.

* The radius of rotation (r_2) of the balancing mass (m_2) is generally made larger in order to reduce the balancing mass.

Unbalanced force,

$$F_U = m\omega^2 r\left(\cos\theta + \frac{\cos 2\theta}{n}\right) = m\omega^2 r\cos\theta + m\omega^2 r \times \frac{\cos 2\theta}{n}$$

The expression ($m\omega^2 r\cos\theta$) is known as *primary unbalanced force* and $m\omega^2 r \times \frac{\cos 2\theta}{n}$ is called *secondary unbalanced force.*

$\therefore$ Primary unbalanced force, $F_P = m\omega^2 r\cos\theta$

and secondary unbalanced force, $F_S = m\omega^2 r \times \frac{\cos 2\theta}{n}$

Notes : **1.** The primary unbalanced force is maximum, when $\theta = 0°$ or $180°$. Thus, the primary force is maximum twice in one revolution of the crank. The maximum primary unbalanced force is given by

$$F_{P(max)} = m\omega^2 r$$

2. The secondary unbalanced force is maximum, when $\theta = 0°, 90°, 180°$ and $360°$. Thus, the secondary force is maximum four times in one revolution of the crank. The maximum secondary unbalanced force is given by

$$F_{S(max)} = m\omega^2 \times \frac{r}{n}$$

3. From above we see that the maximum secondary unbalanced force is $1/n$ times the maximum primary unbalanced force.

4. In case of moderate speeds, the secondary unbalanced force is so small that it may be neglected as compared to primary unbalanced force.

5. The unbalanced force due to reciprocating masses varies in magnitude but constant in direction while due to the revolving masses, the unbalanced force is constant in magnitude but varies in direction.

11.45 Effect of Partial Balancing of Reciprocating Parts of Two Cylinder Locomotives

The reciprocating parts are only partially balanced. Due to this partial balancing of the reciprocating parts, there is an unbalanced primary force along the line of stroke and also an unbalanced primary force perpendicular to the line of stroke. The effect of an unbalanced primary force along the line of stroke is to produce ;

1. Variation in tractive force along the line of stroke ; and 2. Swaying couple.

The effect of an unbalanced primary force perpendicular to the line of stroke is to produce variation in pressure on the rails, which results in hammering action on the rails. The maximum magnitude of the unbalanced force along the perpendicular to the line of stroke is known a *hammer blow.*

The tractive force (F_T) in a locomotive with two cylinders is given by

$$F_T = (1-c)\,m\omega^2 r\,(\cos\theta - \sin\theta)$$

The tractive force is maximum or minimum when $\theta = 135°$ or $315°$.

$\therefore$ Maximum or minimum value of tractive force or variation in tractive force

$$= \pm\,(1-c)\,m\omega^2 r\,(\cos 135° - \sin 135°) = \pm\sqrt{2}\,(1-c)\,m\omega^2 r$$

The swaying couple is due to the primary unbalanced force. Mathematically,

$$\text{Swaying couple} = (1-c)\,m\omega^2 r \times \frac{a}{2}\,(\cos\theta + \sin\theta)$$

The swaying couple is maximum or minimum when $\theta = 45°$ or $225°$.

∴ Maximum and minimum value of the swaying couple

$$= \pm(1-c)m\omega^2 r \times \frac{a}{2}(\cos 45^\circ + \sin 45^\circ) = \pm \frac{a}{\sqrt{2}}(1-c)\,m\omega^2 r$$

11.46 Balancing of Primary Forces of Multi-cylinder In-line Engines

The multi-cylinder engines with the cylinder centre lines in the same plane and on the same side of the centre line of the crankshaft, are known as *In-line engines*. The following two conditions must be satisfied in order to give the primary balance of the reciprocating parts of a multi-cylinder engine :

1. The algebraic sum of the primary forces must be equal to zero. In order words, the primary force polygon must close ; and

2. The algebraic sum of the couples about any point in the plane of the primary forces must be equal to zero. In other words, the primary couple polygon must close.

Note : The closing side of the primary force polygon gives the maximum unbalanced primary force and the closing side of the primary couple polygon gives the maximum unbalanced primary couple.

11.47 Balancing of Secondary Forces of Multi-cylinder In-line Engines

When the connecting rod is not too long (*i.e.* when the obliquity of the connecting rod is considered), then the secondary disturbing force due to the reciprocating mass arises.

We know that the secondary force,

$$F_S = m.\omega^2 .r \times \frac{\cos 2\theta}{n}$$

This expression may be written as

$$F_S = m.(2\omega)^2 \times \frac{r}{4n} \times \cos 2\theta$$

As in case of primary forces, the secondary forces may be considered to be equivalent to the component, parallel to the line of stroke, of the centrifugal force produced by an equal mass placed at the imaginary crank of length $r/4n$ and revolving at twice the speed of the actual crank (*i.e.* 2ω) as shown in Fig. 11.9.

Thus, in multi-cylinder in-line engines, each imaginary secondary crank with a mass attached to the crankpin is inclined to the line of stroke at twice the angle of the actual crank. The values of the secondary forces and couples may be obtained by considering the revolving mass. The following two conditions must be satisfied in order to give a complete secondary balance of an engine :

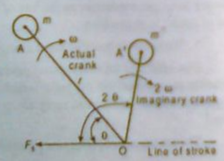


Fig. 11.9

1. The algebraic sum of the secondary forces must be equal to zero. In order words, the secondary force polygon must close, and

2. The algebraic sum of the couples about any point in the plane of the secondary forces must be equal to zero. In other words, the secondary couple polygon must close.

Note : The closing side of the secondary force polygon gives the maximum unbalanced secondary force and the closing side of the secondary couple polygon gives the maximum unbalanced secondary couple.

11.48 Vibrations

When elastic bodies such as a spring, a beam and a shaft are displaced from the equilibrium position by the application of external forces, and then released, they execute a *vibratory motion*.

The following types of vibratory motion are important :

1. *Free or natural vibrations.* When no external force acts on the body, after giving it an initial displacement, then the body is said to be under *free or natural vibrations*. The frequency of the free vibrations is called *free or natural frequency*. The following three types of free vibrations are important :

(*a*) *Longitudinal vibrations.* When the particles of the shaft or disc move parallel to the axis of the shaft, then the vibrations are known as *longitudinal vibrations*. In this case, the shaft is elongated and shortened alternately and thus the tensile and compressive stresses are induced alternately in the shaft.

(*b*) *Transverse vibrations.* When the particles of the shaft or disc move approximately perpendicular to the axis of the shaft, then the vibrations are known as *transverse vibrations*. In this case, the shaft is straight and bent alternately and bending stresses are induced in the shaft.

(*c*) *Torsional vibrations.* When the particles of the shaft or disc move in a circle about the axis of the shaft, then the vibrations are known as *torsional vibrations*. In this case, the shaft is twisted and untwisted alternately and the torsional shear stresses are induced in the shaft.

2. *Forced vibrations.* When the body vibrates under the influence of external force, then the body is said to be under *forced vibrations*. The external force applied to the body is a periodic disturbing force created by unbalance. The vibrations have the same frequency as the applied force.

Note : When the frequency of the external force is same as that of the natural vibrations, resonance takes place.

3. *Damped vibrations.* When there is a reduction in amplitude over every cycle of vibration, the motion is said to be *damped vibration*. This is due to the fact that a certain amount of energy possessed by the vibrating system is always dissipated in overcoming frictional resistances to the motion.

11.49 National Frequency of Free Longitudinal and Transverse Vibrations

The following are the various relations for the natural frequency of free vibrations:

1. The natural frequency of free longitudinal and transverse vibrations is given by

$$f_n = \frac{1}{2\pi}\sqrt{\frac{s}{m}} = \frac{1}{2\pi}\sqrt{\frac{g}{\delta}} = \frac{0.4985}{\sqrt{\delta}} \text{ Hz}$$

where
m = Mass of the body,
s = Stiffness of the body, and
δ = Static deflection of the body.

2. When a shaft of mass (m_c) and stiffness (s) is fixed at one end and carries a mass (m) at the other end, then the natural frequency of its longitudinal vibration is given by

$$f_n = \frac{1}{2\pi}\sqrt{\frac{s}{m + m_c/3}}$$

and the natural frequency of its transverse vibration is given by

$$f_n = \frac{1}{2\pi}\sqrt{\frac{s}{m + 33m_c/140}}$$

3. The natural frequency of free transverse vibrations due to a point load acting on a simply supported shaft is given by

$$f_n = \frac{0.4985}{\sqrt{\delta}} \text{ Hz}$$

and due to uniformly distributed load,

$$f_n = \frac{0.5615}{\sqrt{\delta_s}} \text{ Hz}$$

where δ and δ_s are the static deflections of simply supported shaft due to the point load and uniformly distributed load respectively.

4. The natural frequency of free transverse vibrations of a shaft fixed at both ends and carrying a uniformly distributed load is given by

$$f_n = \sqrt{\frac{0.571}{\delta_s}} \text{ Hz}$$

where δ_s = Static deflection of shaft fixed at both ends and carrying a uniformly distributed load.

11.50 Critical or Whirling Speed of a Shaft

The speed at which the shaft runs so that the additional deflection of the shaft from the axis of rotation becomes infinite, is known as *critical* or *whirling speed*. It is equal to the natural frequency of transverse vibrations but its unit will be revolutions per second (r.p.s.)

11.51 Frequency of Free Damped Vibrations (Viscous Damping)

We know that the motion of a body is resisted by frictional forces. In vibrating systems, the effect of friction is referred to as damping. The damping provided by fluid resistance is known as *viscous damping*.

The equation of motion for a vibrating system with viscous damping is

$$\frac{d^2x}{dt^2} + \frac{c}{m} \times \frac{dx}{dt} + \frac{s}{m} \times x = 0$$

It may be noted that

1. If the roots of this equation are real, then the system will the *overdamped*.

2. If the roots are complex conjugate, then the system will be *under damped* and it is a practical case of damping. In under damped vibrating system, the amplitude of vibration decreases exponentially with time. If x_1 and x_2 are the successive values of the amplitude on the same side of the mean position, then logarithmic decreament is equal to $\log\left(\frac{x_1}{x_2}\right)$.

3. If the roots are equal, then the system will be *critically damped*.

11.52 Vibration Isolation and Transmissibility

When an unbalanced machine is installed on the foundation, it produces vibration in the foundation. In order to prevent these vibrations or to minimise the transmission of forces to the foundation, the machines are mounted on springs and dampers or on some vibration isolating material

as shown in Fig. 11.10. The arrangement is assumed to have one degree of freedom, *i.e.* it can move up and down only.

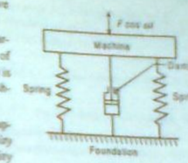


Fig. 11.10

It may be noted that when a periodic (*i.e.* simple harmonic) disturbing force $F \cos \omega t$ is applied to a machine of mass m supported by a spring of stiffness s, then the force is transmitted by means of the spring and the damper or dash-pot to the fixed support or foundation.

The ratio of the force transmitted (F_T) to the force applied (F) is known as the *isolation factor* or *transmissibility ratio* of the spring support. Mathematically, transmissibility ratio,

$$\varepsilon = \frac{F_T}{F}$$

When damper is not provided, then transmissibility ratio is given by

$$\varepsilon = \frac{1}{1-(\omega/\omega_n)^2}$$

From above, we see that when $\omega/\omega_n > 1$, ε is negative. This means that there is a phase difference of 180° between the transmitted force and the disturbing force ($F \cos \omega t$). The value of ω/ω_n must be greater than $\sqrt{2}$ if ε is to be less than 1 and it is the numerical value of ε, independent of any phase difference between the forces that may exist which is important. It is, therefore, more convenient to use the above equation in the following form, *i.e.*

$$\varepsilon = \frac{1}{(\omega/\omega_n)^2 - 1}$$

11.53 Natural Frequency of Free Torsional Vibrations

The natural frequency of free torsional vibrations of a shaft is given by

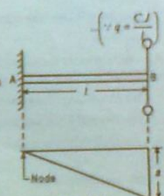
$$f_n = \frac{1}{2\pi}\sqrt{\frac{q}{I}}$$

where q = Torsional stiffness of the shaft in N-m, and

I = Mass moment of inertia of the disc in kg-m² $= m.k^2$

Consider a shaft fixed at one end and carrying a rotor at the free end, as shown in Fig. 11.11. The natural frequency of torsional vibration,

$$f_n = \frac{1}{2\pi}\sqrt{\frac{q}{I}} = \frac{1}{2\pi}\sqrt{\frac{CJ}{lI}}$$



where C = Modulus of rigidity for shaft material,

J = Polar moment of inertia of shaft $= \frac{\pi}{32} \times d^4$

d = Diameter of shaft,

l = Length of shaft,

m = Mass of rotor,

k = Radius of gyration of rotor, and

I = Mass moment of inertia of rotor $= m.k^2$

Fig. 11.11

A little consideration will show that the amplitude of vibration is zero at A and maximum at B, as shown in Fig. 11.11. It may be noted that the point or the section of the shaft whose amplitude of torsional vibration is zero, is known as *node*. In other words, at the *node*, the shaft remains unaffected by the vibration.

Note: A shaft carrying two rotors at its ends, will have one node and a shaft carrying three rotors will have two nodes.

11.54 Torsionally Equivalent Shaft

When a shaft has variable diameters for different length as shown in Fig. 11.12 (*a*), then it should be replaced by an equivalent shaft of uniform diameter, as shown in Fig. 11.12 (*b*).

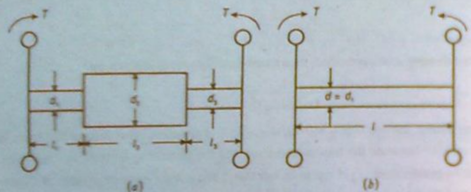


Fig. 11.12

The length of an equivalent shaft is given by

$$l = l_1 + l_2\left(\frac{d_1}{d_2}\right)^4 + l_3\left(\frac{d_1}{d_3}\right)^4$$

OBJECTIVE TYPE QUESTIONS

1. In a reciprocating steam engine, which of the following forms a kinematic link?
   (*a*) Cylinder and piston (*b*) Piston rod and connecting rod
   (*c*) Crankshaft and flywheel (*d*) Flywheel and engine frame
2. A link or element need not to be a rigid body, but it must be a resistant body.
   (*a*) Agree (*b*) Disagree
3. A railway bridge is an example of a machine.
   (*a*) True (*b*) False
4. The motion between a pair when limited to a definite direction, irrespective of the direction of force applied, is known as
   (*a*) completely constrained motion (*b*) incompletely constrained motion
   (*c*) successfully constrained motion (*d*) none of these
5. The motion between a pair which takes place in.........is known as incompletely constrained motion.
   (*a*) one direction only (*b*) more than one direction

6. When the connection between the elements forming a pair is such that the constrained motion is not completed by itself, but by some other means, the motion is said to be a completely constrained motion.
   (*a*) Yes (*b*) No
7. The example of completely constrained motion is a
   (*a*) motion of a piston in the cylinder of a steam engine
   (*b*) motion of a square bar in a square hole
   (*c*) motion of a shaft with collars at each end in a circular hole
   (*d*) all of the above
8. The motion of a shaft in a circular hole is an example of
   (*a*) completely constrained motion (*b*) incompletely constrained motion
   (*c*) successfully constrained motion (*d*) none of these
9. The example of successfully constrained motion is a
   (*a*) motion of an I.C. engine valve
   (*b*) motion of the shaft between a foot-step bearing
   (*c*) piston reciprocating inside an engine cylinder
   (*d*) all of the above
10. Which of the following statement is wrong?
    (*a*) A round bar in a round hole form a turning pair.
    (*b*) A square bar in a square hole form a sliding pair.
    (*c*) A vertical shaft in a foot step bearing forms a successful constraint.
    (*d*) all of the above
11. When the nature of contact between the elements of a pair is such that it can only slide relative to the other, the pair is known as a
    (*a*) screw pair (*b*) spherical pair (*c*) turning pair (*d*) sliding pair
12. When the nature of contact between the elements of a pair is such that it can turn or revolve about a fixed axis, the pair is known as a rolling pair.
    (*a*) Correct (*b*) Incorrect
13. When the nature of contact between the elements of a pair is such that one element can turn about the other by screw threads, the pair is known as a
    (*a*) screw pair (*b*) spherical pair (*c*) turning pair (*d*) sliding pair
14. A sliding pair has a completely constrained motion.
    (*a*) Yes (*b*) No
15. Which of the following is an example of sliding pair?
    (*a*) Piston and cylinder of a reciprocating steam engine.
    (*b*) Shaft with collars at both ends fitted into a circular hole.
    (*c*) Lead screw of a lathe with nut.
    (*d*) Ball and a socket joint.
16. The ball and socket joint is an example of screw pair.
    (*a*) Agree (*b*) Disagree

12

Machine Design

12.1 Introduction

The subject Machine design is the creation of new and better machines and improving the existing ones. A new or better machine is one which is more economical in the overall cost of production and operation.

The knowledge of materials and their properties is of great significance for a design engineer. The following are some mechanical properties of metals which are associated with the ability of the material to resist mechanical forces and load :

1. *Elasticity.* It is the property of a material to regain its original shape after deformation when the external forces are removed.

2. *Plasticity.* It is the property of a material which retains the deformation produced under load permanently.

3. *Ductility.* It is the property of a material enabling it to be drawn into wire with the application of a tensile force.

4. *Brittleness.* It is the property of breaking of a material with little permanent distortion.

5. *Malleability.* It is a special case of ductility which permits materials to be rolled or hammered into thin sheets.

6. *Toughness.* It is the property of a material to resist fracture due to high impact loads like hammer blows.

12.2 Ferrous Metals

The ferrous metals are those which have iron as their main constituent. The ferrous metals commonly used in engineering practice are cast iron, wrought iron, steels and alloy steels. These ferrous metals are discussed, in brief, as follows:

1. *Cast iron.* The carbon contents in cast iron varies from 1.7 percent to 4.5 percent. It also contains small amounts of silicon, manganese, phosphorus and sulphur. The various types of cast irons, in use, are as follows:

(*a*) *Grey cast iron.* It contains 3 to 3.5 percent carbon. The grey colour is due to the fact that carbon is present in the form of free graphite. It is widely used for machine tool bodies, flywheels, pipes and pipe fittings etc.

(*b*) *White cast iron.* It contains 1.75 to 2.3 percent carbon. The white colour is due to the fact that it has no graphite and whole of the carbon is in the form of carbide (known as cementite).

(*c*) *Mottled cast iron.* It is a product between grey and white cast iron in composition, colour and general properties.

(*d*) *Malleable cast iron.* It is a cast iron-carbon alloy which solidifies in the as-cast condition in a graphite free structure.

2. *Wrought iron.* It is the purest iron which contains at least 99.5% iron. It is tough, malleable

and ductile material. It can not stand sudden and excessive shocks. It can be easily forged or welded. It is used for chains, crane hooks, railway couplings, water and steam pipes.

3. *Steel.* It is an alloy of iron and carbon, with carbon content up to a maximum of 1.5%. The carbon occurs in the form of iron carbide, because of its ability to increase the hardness and strength of the steel. Other elements *e.g.*, silicon, sulphur, phosphorus and manganese are also present to greater or lesser amount to impart certain desired properties to it. Most of the steel produced now-a-days is *plain carbon steel* or simply *carbon steel*. A carbon steel is defined as a steel which has its properties mainly due to its carbon content and *does not contain more than* 0.5% of silicon and 1.5% of manganese. The plain carbon steels varying from 0.06% carbon to 1.5% carbon are divided into the following types depending upon the carbon content.

(*a*) Dead mild steel — up to 0.15% carbon

(*b*) Low carbon or mild steel — 0.15% to 0.45% carbon

(*c*) Medium carbon steel — 0.45% to 0.8% carbon

(*d*) High carbon steel — 0.8 % to 1.5% carbon

Note: Steel containing 0.8% carbon is known as *eutectoid steel*. Steel containing less than 0.8% carbon is called *hypo-eutectoid steel* and steel containing above 0.8% carbon is called *hyper - eutectoid steel*.

4. *Alloy Steel.* An alloy steel may be defined as a steel to which elements other than carbon are added in sufficient amount to produce an improvement in properties. The alloying is done for specific purposes to increase wearing resistance, corrosion resistance and to improve electrical and magnetic properties, which cannot be obtained in plain carbon steels. The chief alloying elements used in steel are nickel, chromium, molybdenum, cobalt, vanadium, manganese, silicon and tungsten. Each of these elements confer certain qualities upon the steel to which it is added. These elements may be used separately or in combination to produce the desired characteristic in steel.

12.3 Heat Treatment of Steels

The term heat treatment may be defined as an operation or a combination of operations, involving the heating and cooling of a metal or an alloy in the solid state for the purpose of obtaining certain desirable conditions or properties without change in chemical composition. The aim of heat treatment is to achieve one or more of the following objects :

1. To increase the hardness of metals.
2. To relieve the stresses set up in the material after hot or cold working.
3. To improve machinability.
4. To soften the metal.
5. To modify the structure of the material to improve its electrical and magnetic properties.
6. To change the grain size.
7. To increase the qualities of a metal to provide better resistance to heat, corrosion and wear.

Following are the various heat treatment processes commonly employed in engineering practice:

(*a*) Normalising ; (*b*) Annealing ; (*c*) Spheroidising ; (*d*) Hardening ; (*e*) Tempering ; and (*f*) Surface hardening or Case hardening.

12.4 Interchangeability

The term interchangeability is normally employed for the mass production of identical items within the prescribed limits of sizes. In order to control the size of finished part with due allowance for error for interchangeable parts is called *limit system*. The various important terms used in limit system (or interchangeable system) are as follows:

1. *Nominal size.* It is the size of a part specified in the drawing as a matter of convenience.

2. *Basic size.* It is the size of a part to which all limits of variation (*i.e.* tolerances) are applied to arrive at final dimensioning of the mating parts. The nominal or basic size of a part is often the same.

3. *Actual size.* It is the actual measured dimension of the part.

4. *Limits of sizes.* There are two extreme permissible sizes for a dimension as shown in Fig. 12.1. The largest permissible size for a dimension is called *upper or high limit* whereas the smallest size is known as *lower limit*.

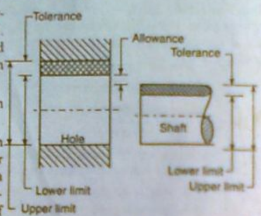


Fig. 12.1

5. *Allowance.* It is the difference between the basic dimensions of the mating parts.

6. *Tolerance.* It is the difference between the upper limit and lower limit of a dimension. In other words, it is the maximum permissible variation in a dimension. The tolerance may be *unilateral* or *bilateral*. When all the tolerance is allowed on one side of the nominal size, *e.g.* $20^{+0.004}_{-0.000}$, then it is said to be *unilateral system of tolerance*. The unilateral system is mostly used in industries as it permits changing the tolerance value while still retaining the same allowance or type of fit.

When the tolerance is allowed on both sides of the nominal size, *e.g.* $20^{+0.002}_{-0.002}$, then it is said to be *bilateral system of tolerance*. In this case + 0.002 is the uper limit and –0.002 is the lower limit.

7. *Tolerance zone.* It is the zone between the maximum and minimum limit size, as shown in Fig. 12.2.

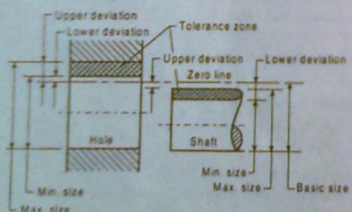


Fig. 12.2

8. *Zero line.* It is a straight line corresponding to tne basic size. The deviations are measured from this line. The positive and negative deviations are shown above and below the zero line respectively.

9. *Upper deviation.* It is the algebraic difference between the maximum limit and the basic size.

10. *Lower deviation.* It is the algebraic difference between the minimum limit and the basic size.

11. *Actual deviation.* It is the algebraic difference between an actual size and the corresponding basic size.

12. *Mean deviation.* It is the arithmetical mean between the upper and lower deviations.

13. *Fundamental deviation.* It is one of the two deviations which is conventionally chosen to define the position of the tolerance zone in relation to zero line, as shown in Fig. 12.3.

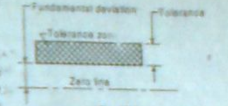


Fig. 12.3

12.5 Fits

The degree of tightness or looseness between the two mating parts is known as a *fit* of the parts. The nature of fit is characterised by the presence and size of clearance and interference. The *clearance* is the amount by which the actual size of the shaft is less than the actual size of the mating hole in an assembly. The *interference* is the amount by which the actual size of a shaft is larger than the actual size of the mating hole in an assembly. The *allowance* is an intentionally prescribed difference between the lower limit and the upper limit of a size.

According to Indian standards, the fits are classified as clearance fits, interference fits and transition fits.

12.6 Basis of Limit System

The following are two bases of limit system :

1. *Hole basis system.* When the hole is kept as a constant member and different fits are obtained by varying the shaft size, then the limit system is said to be on a hole basis.

2. *Shaft basis system.* When the shaft is kept as a constant member and different fits are obtained by varying the hole size, then the limit system is said to be on a shaft basis.

According to Indian standards, the system of limits and fits comprise 18 grades of fundamental tolerances which are designated as IT 01, IT 0, and IT 1 to IT 16. These are called standard tolerances. The standard tolerances for grades IT5 to IT7 are determined in terms of standard tolerance unit (i) in microns, where

i (microns) $= 0.45\sqrt[3]{D} + 0.001\,D$, where D is the size or diameter in mm.

The values of standard tolerances corresponding to grades IT01, IT0 and IT1 are as given below :

For IT01, i (microns) $= 0.3 + 0.008\,D$,

For IT0, i (microns) $= 0.5 + 0.012\,D$, and

For IT1, i (microns) $= 0.8 + 0.020\,D$,

where D is the size or diameter in mm.

12.7 Theories of Failure Under Static Load

We know that strength of machine members is based upon the mechanical properties of the materials used. Since these properties are usually determined from simple tension or compression tests, therefore, predicting failure in members subjected to uni-axial stress is both simple and straightforward. But the problem of predicting the failure stresses for members subjected to bi-axial or tri-axial stresses is much more complicated. In fact, the problem is so complicated that a large number of different theories have been formulated. The principal theories of failure for a member subjected to bi-axial stress are as follows :

1. *Maximum principal or normal stress theory (Rankine's Theory)* According to this theory, the failure or yielding occurs at a point in a member when the maximum principal or normal stress in a bi-axial stress system reaches the limiting strength of the material in a simple tension test.

2. *Maximum shear stress theory (Guest's theory)* According to this theory, the failure or yielding occurs at a point in a member when the maximum shear stress in a bi-axial stress system reaches a value equal to the shear stress at yield point in a simple tension test.

3. *Maximum principal strain theory (Saint Venant's theory).* According to this theory, the failure or yielding occurs at a point in a member when the maximum principal (or normal) strain in a bi-axial stress system reaches the limiting value of strain (*i.e.* strain at yield point) as determined from a simple tension test.

4. *Maximum strain energy theory (Haigh's theory).* According to this theory, the failure or yielding occurs at a point in a member when the strain energy per unit volume in a bi-axial stress system reaches the limiting strain energy (*i.e.* strain energy at yield point) per unit volume as determined from a simple tension test.

5. *Maximum distortion energy theory (Hencky and Von Mises theory).* According to this theory, the failure or yielding occurs at a point in a member when the distortion strain energy (also called shear strain energy) per unit volume in a bi-axial stress system reaches the limiting distortion energy (*i.e.* distortion energy at yield point) per unit volume as determined from a simple tension test.

12.8 Fatigue and Endurance Limit

When a material is subjected to repeated stresses, it fails at stresses below the yield point stresses. Such type of failure of a material is known as *fatigue*. The endurance or fatigue limit is defined as the maximum value of the completely reversed bending stress which a polished standard specimen can withstand without failure, for infinite number of cycles (usually 10^7 cycles).

The endurance limit of the material depends upon many factors such as surface finish factor, size factor, load factors, etc. It may be noted that for a mirror polished material, the surface finish factor is unity.

It has been found experimentally that endurance limit (σ_e) of a material subjected to fatigue loading is a function of ultimate tensile strength (σ_u). Following are some empirical relations commonly used in practice:

For steel, $\sigma_e = 0.5\ \sigma_u$; For cast steel, $\sigma_e = 0.4\ \sigma_u$; For cast iron, $\sigma_e = 0.35\ \sigma_u$;

For non-ferrous metals and alloys, $\sigma_e = 0.3\ \sigma_u$.

When a component is subjected to fatigue loading, the endurance limit is the criterion for failure. Therefore, the factor of safety should be based on endurance limit which is defined as the ratio of endurance limit to the working stress.

12.9 Stress Concentration

Whenever a machine component changes the shape of its cross-section, the simple stress distribution no longer holds good and the neighbourhood of the discontinuity is different. This irregularity in the stress distribution caused by abrupt changes of form is called *stress concentration*. It occurs for all kinds of stresses in the presence of fillets, notches, holes, keyways, splines, surface roughness or scratches etc.

The ratio of the maximum stress in a member (at a notch or a fillet) to the nominal stress at the same section, is called *theoretical or form stress concentration factor*. Its value depends upon the material and geometry of the part.

Notes: 1. In static loading, the stress concentration in ductile materials is not so serious as in brittle materials because in ductile material, local deformation or yielding takes place which reduces the concentration.

2. In cyclic loading, the stress concentration in ductile materials is always serious because the ductility of the material is not effective in relieving the concentration of stress caused by cracks, flaws, etc.

3. The ratio of endurance limit without stress concentration to the endurance limit with stress concentration is known as *fatigue stress concentration factor*.

12.10 Pressure Vessels

The pressure vessels (*i.e.* cylinders or tanks) are used to store fluids under pressure. The fluid being stored may undergo a change of state inside the pressure vessel as in case of steam boilers or it may combine with other reagents as in a chemical plant. The material of pressure vessels may be brittle such as cast iron or ductile such as mild steel.

According to the dimensions, the pressure vessels may be classified as *thin shell* or *thick shell*. If the wall thickness (t) of the shell is less than 1 / 10 of the diameter of the shell (d), then it is called a *thin shell*. On the other hand, if the wall thickness (t) of the shell is more than 1 / 10 of the diameter of the shell, then it is called a *thick shell*.

According to the end construction, the pressure vessels may be classified as *open end* or *closed end*. In case of vessels having open ends, the circumferential or hoop stresses are induced by the fluid pressure, where as in case of closed ends, longitudinal stresses in addition to circumferential stresses are induced.

The following points are worthnoting in connection with pressure vessels.

1. The design of pressure vessels is based on hoop stress.
2. The longitudinal stress is one-half of the circumferential stress.
3. In designing thick cylindrical shells, the following equations are used:

(*a*) Lame's equation; (*b*) Birnie's equation; (*c*) Clavarino's equation; and (*d*) Barlow's equation.

4. In case of thick cylinders, the tangential stress across the thickness of the cylinder is maximum at the inner surface and minimum at the outer surface.

5. The radial stress across the thickness of the cylinder is maximum at the inner surface and zero at the outer surface.

12.11 Pipes and Pipe Joints

The pipes are used for transporting various fluids like water, steam, different types of gases, oil and other chemicals with or without pressure, from one place to another. These are usually connected to vessels from which they transport the fluid. Since the length of pipes available are limited, therefore various lengths of pipes have to be joined to suit any particular installation. The following pipe joints are mostly used in practice:

1. *Socket or a coupler joint.* This joint is mostly used for pipes carrying water at low pressure and where the overall smallness of size is most essential.

2. *Nipple joint.* This joint has the disadvantage of reducing the area of flow.

3. *Union joint.* This joint provides the facility of disengaging the pipes by simply unscrewing a coupler nut.

4. *Spigot and socket joint.* This joint is chiefly used for pipes which are buried in the earth.

5. *Expansion joint.* This joint is mostly used for pipes carrying steam at high pressures

6. *Flanged joint.* It is one of the most widely used pipe joint. A flanged joint may be made with flanges cast integral with pipes or loose flanges welded or screwed.

7. *Hydraulic pipe joint.* This type of joint has oval flanges and are fastened by two bolts. Such joints are used to carry fluid pressure varying from 5 to 14 N / mm^2.

12.12 Riveted Joints

A rivet is a short cylindrical bar with a head integral to it. The rivets are used to make permanent fastening between the plates. The riveting may be done by hand or by a riveting machine. Though there are many types of rivet heads, yet the snap heads are usually employed for structural work and machine riveting. The following are the two types of riveted joints, depending upon the way in which the plates are connected.

1. *Lap joint.* A lap joint is that in which one plate overlaps the other and the two plates are riveted together.

2. *Butt joint.* A butt joint is that in which the main plates are kept in alignment butting (*i.e.* touching) each other and a cover plate (*i.e.* strap) is placed either on one side or on both sides of the main plates. The cover plate is then riveted together with the main plates.

The butt joints may be single strap butt joint or double strap butt joint. Depending upon the number of rows of rivets, the butt joints may be single riveted or double riveted. It may also be triple riveted or quadruple riveted.

When the rivets in the various rows are opposite to each other, then the joint is said to be *chain riveted*. On the other hand, if the rivets in the adjacent rows are staggered in such a way that every rivet is in the middle of the two rivets of the opposite row, then the joint is said to be *zig-zag riveted*.

In order to make the joint leak proof or fluid tight in pressure vessels like steam boilers, a process known as *caulking* is employed. A more satisfactory way of making the joints staunch is known as *fullering*, which has largely superseded caulking.

Following are some important terms used in connection with riveted joints:

(*a*) *Pitch.* It is the distance from the centre of one rivet to the centre of the next rivet measured parallel to the seam.

(*b*) *Back pitch.* It is the perpendicular distance between the centre lines of the successive rows.

(*c*) *Diagonal pitch.* It is the distance between the centres of the rivets in adjacent rows of zig-zag riveted joints.

(*d*) *Margin or marginal pitch.* It is the distance between the centre of rivet hole to the nearest edge of the plate.

12.13 Failures of a Riveted Joint

A riveted joint may fail in the following ways:

1. *Tearing of the plate at an edge.* A joint may fail due to tearing of the plate at an edge. This can be avoided by keeping the margin, $m = 1.5\ d$, where d is the diameter of rivet hole.

2. *Tearing of the plate across a row of rivets.* Due to the tensile stresses in the main plates, the main plate or cover plates may tear off across a row of rivets. The tearing resistance or pull required to tear off the plate per pitch length is given by

$$P_t = (p - d)\, t\, \sigma_t$$

where
p = Pitch of the rivets,
d = Diameter of the rivet hole,
t = Thickness of the plate, and
σ_t = Permissible tensile stress for the plate material.

3. *Shearing of the rivets.* The plates which are connected by the rivets exert tensile stress on the rivets, and if the rivets are unable to resist the stress, then they are sheared off. It may be noted that the rivets are always in single shear in case of lap joints and in single cover butt joints. But the rivets are in double shear in a double cover butt joint. The shearing resistance or pull required to shear off the rivet per pitch length is given by

$$P_s = n \times \frac{\pi}{4} \times d^2 \times \tau \quad \text{...(In single shear)}$$

$$= n \times 2 \times \frac{\pi}{4} \times d^2 \times \tau \quad \text{...(Theoretically, in double shear)}$$

$$= n \times 1.875 \times \frac{\pi}{4} \times d^2 \times \tau \quad \text{...(In double shear, according to Indian Boiler Regulations)}$$

where
n = Number of rivets per pitch length, and
τ = Safe permissible shear stress for the rivet material.

4. *Crushing of the rivets.* Sometimes, the rivets do not actually shear off under the tensile stress, but are crushed. Due to this, the rivet hole becomes of an oval shape and hence the joint becomes loose. The crushing resistance or pull required to crush the rivet per pitch length is given by

$$P_c = n\, .\, d.\, t.\, \sigma_c$$

where σ_c = Safe permissible crushing stress for the rivet or plate material.

Notes: 1. The number of rivets in shear shall be equal to the number of rivets under crushing.

2. The least value of P_t, P_s and P_c is known as the strength of the riveted joint.

3. The strength of the un-riveted or solid plate (P) per pitch length is given by

$$P = p.\, t.\, \sigma_t$$

4. The ratio of the strength of the riveted joint to the strength of the un-riveted or solid plate per pitch length is called efficiency of the riveted joint.

12.14 Design of Boiler Joints

The boiler has a longitudinal joint as well as circumferential joint. The longitudinal joint is used to join the ends of the plate to get the required diameter of a boiler. For this purpose, a butt joint with two cover plates is used. The circumferential joint is used to get the required length of the boiler. For this purpose, a lap joint with one ring over lapping the other alternately is used.

According to Indian Boiler Regulations (*I.B.R.*), the following procedure should be adopted for the design of longitudinal butt joint for a boiler.

1. *Thickness of boiler shell.* The thickness of the boiler shell is determined by the thin cylinderical formula, *i.e.*

$$t = \frac{P.D}{2\sigma_t . \eta_l} + 1 \text{ mm as corrosion resistance}$$

where

P = Steam pressure in boiler,

D = Internal diameter of boiler shell,

σ_t = Permissible tensile stress, and

η_l = Efficiency of the longitudinal joint.

It may be noted that

(*a*) The thickness of the boiler shell should not be less than 7 mm.

(*b*) The efficiency of a double riveted double strap (of equal width) butt joint is from 70 to 83% and the efficiency of a triple riveted butt joint with double straps of unequal width (5 rivets per pitch length) is 80 to 90%.

(*c*) The factor of safety should not be less than 4.

2. *Diameter of rivets.* The diameter of the rivet hole (d) may be determined by using Unwin's empirical formula, *i.e.*

$$d = 6\sqrt{t} \text{ (when } t \text{ is greater than 8 mm)}$$

If the thickness of the plate is less than 8 mm, then the diameter of the rivet hole may be calculated by equating the shearing resistance of the rivets to the crushing resistance. In no case, the diameter of the rivet hole should not be less than the thickness of the plate.

According to Indian standards, the diameter of the rivet hole is made larger than the basic size of the rivet as follows:

1 mm larger for rivets of 12, 14, 16, 18, 20, 22 and 24 mm,

1.5 mm larger for rivets of 27, 30, 33, 36 mm, and

2 mm larger for rivets of 39, 42, 48 mm

3. *Pitch of rivets.* The pitch of rivets is obtained by equating the tearing resistance of the plate to the shearing resistance of the rivets. It should not be less than 2 d.

The maximum value of the pitch of rivets for a longitudinal joint of a boiler as per I.B.R. is given by

$$p_{max} = C.t + 41.28 \text{ mm}$$

where C = A constant

4. *Distance between the rows of rivets.* For equal number of rivets in more than one row for lap joint or butt joint, the distance between the rows of rivets should not be less than 2 d for chain riveting and $0.33p + 0.67\,d$, for zig-zag riveting.

5. *Thickness of butt strap.* The thickness of butt strap, in no case, shall be less than 10 mm.

For unequal width of butt straps, the thicknesses of butt straps are

t_1 = 0.75 t, for wide strap on the inside, and

t_2 = 0.625 t, for narrow strap on the outside.

6. The margin is taken as 1.5 d.

12.15 Welded Joints

A welded joint is a permanent joint which is obtained by the fusion of the edges of the two parts to be joined together, with or without the application of pressure and a filler material. The following two types of welded joints are important:

1. Lap joint or fillet joint, and 2. Butt joint.

The transverse fillet welded joints are designed for tensile strength whereas the parallel fillet welded joints are designed for shear strength.

The tensile strength of a double transverse fillet weld, as shown in Fig. 12.4 (*a*), is given by

$$P = 1.414\, s \times l \times \sigma_t$$

and shear strength of a double parallel fillet weld as shown in Fig. 12.4 (*b*),

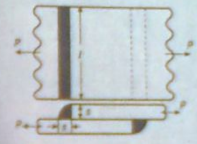
$$P = 1.414\, s \times l \times \tau$$

where

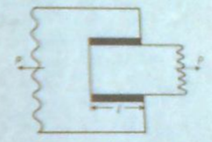
s = Leg or size of weld,

l = Length of weld,

σ_t and τ = Allowable tensile and shear stress respectively.



(*a*) Double transverse fillet weld.



(*b*) Double parallel fillet weld.

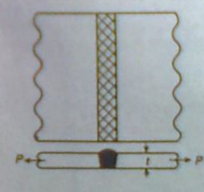
Fig. 12.4

The butt joints are designed for tension or compression. Consider a single V-butt joint as shown in Fig. 12.5 (*a*).

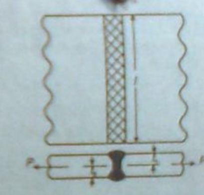
In case of butt joint, the length of leg or size of weld is equal to the throat thickness which is equal to the thickness of plates.

Tensile strength of the butt joint (single V or square butt joint),

$$P = t \times l \times \sigma_t$$



(*a*) Single V-butt joint.



(*b*) Double V-butt joint.

Fig. 12.5

and tensile strength for double V- butt joint as shown in Fig. 12.5 (*b*), is given by

$$P = (t_1 + t_2)\, l \times \sigma_t$$

where l = Length of weld. It is generally equal to width of plates.

t_1 = Throat thickness at the top, and

t_2 = Throat thickness at the bottom.

12.16 Screwed Joints

A screwed joint is mainly composed of two elements, *i.e.*, a bolt and nut. The screwed joints are widely used where the machine parts are required to be readily connected or disconnected without damage to the machine or fastening.

The following terms used in screw threads, as shown in Fig. 12.6, are important:

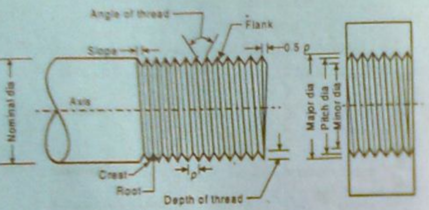


Fig. 12.6

1. *Major diameter.* It is the largest diameter of an external or internal screw thread. The screw is specified by this diameter. It is also known as *outside* or *nominal diameter*.

2. *Minor diameter.* It is the smallest diameter of an external or internal screw thread. It is also known as *core* or *root diameter*.

3. *Pitch diameter.* In a nut and bolt assembly, it is the diameter at which the ridges on the bolt are in complete touch with the ridges of the corresponding nut. It is also called an *effective diameter*.

4. *Pitch.* It is the distance from a point on one thread to the corresponding point on the next thread.

5. *Lead.* It is the distance which a screw thread advances axially in one rotation of the nut. It is equal to pitch in case of single start threads, it is twice the pitch in double start, thrice the pitch in triple start and so on.

6. *Crest.* It is the top surface of the thread.

7. *Root.* It is the bottom surface created by two adjacent flanks of the thread.

8. *Depth of thread.* It is the perpendicular distance between the crest and root.

9. *Flank.* It is the surface joining the crest and root.

10. *Angle of thread.* It is the angle included by the flanks of the thread.

11. *Slope of thread.* It is equal to one-half the pitch of the thread.

12.17 Forms of Screw Threads

The following are various forms of screw threads:

1. *British standard whitworth (B.S.W.) threads.* It is a symmetrical V-thread in which the angle between the flanks, measured in an axial plane, is 55°. These threads are found on bolts and screwed fastenings for special purposes.

2. *British association (B.A.) thread.* It is a B.S.W. thread with fine pitches. The included angle for this thread is $47\frac{1}{2}^\circ$. These threads are used for instruments and other precision works.

3. *American national standard thread.* It is also known as U.S. or Seller's thread and has flat crests and roots. The included angle is 60°. These threads are used for general purposes *e.g.* on bolts, nuts, screws and tapped holes.

4. *Unified standard thread.* This thread has rounded crests and roots, with the included angle of 60°.

5. *Square thread.* The square threads, because of their high efficiency, are widely used for transmission of power in either direction. Such type of threads are usually found on the feed mechanism of machine tools, valves, spindles, screw jacks etc. The square threads are not so strong as V-threads, but they offer less frictional resistance to motion than whitworth threads.

6. *Acme thread.* It is a modification of square thread. It is much stronger than square thread. These threads are frequently used on screw cutting lathes, brass valves, cocks and bench vices.

7. *Knuckle thread.* It is also a modification of square thread. It has rounded top and bottom. These threads are usually found on railway carriage couplings, hydrants, neck of glass bottles etc.

8. *Buttress thread.* It is used for transmission of power in one direction only. It has a low frictional resistance characteristics of the square thread and have the same strength as that of V-thread. The spindles of bench vices are usually provided with buttress thread.

9. *Metric thread.* It is an Indian standard thread and is similar to B.S.W. threads. It has an included angle of 60° instead of 55°.

12.18 Common Types of Screw Fastenings

Following are the common types of screw fastenings:

1. *Through bolt.* A through bolt (or simply a bolt) has a cylindrical bar with threads for the nut at one end and head at the other end.

2. *Tap bolt.* A tap bolt or screw differs from a bolt. It is screwed into a tapped hole of one of the parts to be fastened without the nut.

3. *Studs.* A stud is a round bar threaded at both ends.

4. *Cap screws.* The cap screws are similar to tap bolts except that they are of small size and a variety of shapes of heads are available.

5. *Machine screws.* These are similar to cap screws with head slotted for the screw driver. These are generally used with a nut.

6. *Set screws.* These are used to prevent relative motion between the two parts.

12.19 Locking Devices

A large number of locking devices are available, some of which are as follows:

1. Jam nut or locknut; 2. Castle nut; 3. Sawn nut; 4. Penn, ring or grooved nut; 5. Locking with pin; 6. Locking with plate; and 7. Spring lock washer.

12.20 Designation of Screw Threads

According to Indian standards, the complete designation of the screw thread include

1. *Size designation.* The size of the screw thread is designated by the letter '*M*' followed by the diameter and pitch, the two being separated by the sign ×.

2. *Tolerance designation.* This shall include

(*a*) A figure designating tolerance grade, as indicated below:

'7' for fine grade, '8' for normal (medium) grade, and '9' for coarse grade.

(*b*) A letter designating the tolerance position as indicated below:

'*H*' for unit thread, '*d*' for bolt thread with allowance, and '*h*' for bolt thread without allowance.

For example, a bolt thread of 6 mm size of coarse pitch and with allowance on threads and normal (medium) tolerance grade is designated as $M6-8\,d$.

12.21 Stresses in Screwed Fastening due to Static Loading

The following stresses in screwed fastening due to static loading are important:

1. *Initial stresses due to screwing up forces.* The initial stresses induced in a bolt, screw or stud, when it is screwed up tightly are as follows:

(*a*) Tensile stress due to stretching of bolt,

(*b*) Torsional shear stress caused by the frictional resistance of the threads during its tightening,

(*c*) Shear stress across the threads,

(*d*) Compression or crushing stress on threads,

(*e*) Bending stress if the surfaces under the head are not perfectly parallel to the bolt axis.

It has been found by experiments that the initial tension in a bolt (P_i) is

$$P_i = 2840\,d \text{ N} \qquad \text{... (For a fluid tight joint)}$$

$$= 1420\,d \text{ N} \qquad \text{... (For an ordinary joint)}$$

where d = Nominal diameter of bolt in mm.

The small diameter bolts may fail during tightening, therefore, bolts of smaller diameter (less than $M16$ or $M18$) are not permitted for making fluid tight joints.

2. *Stresses due to external forces.* When a bolt is subjected to an external load, the following stresses are induced:

(*a*) Tensile stress ; (*b*) Shear stress ; and (*c*) Combined tensile and shear stress.

3. *Stresses due to combined forces.* The resultant axial load on a bolt depends upon the following factors:

(*a*) The initial tension due to tightening of the bolt (P_1)

(*b*) The external load (P_2), and

(*c*) The relative elastic yielding (springiness) of the bolt and the connected members.

When the connected members are very yielding as compared with the bolt, which is a soft gasket, then the resultant load on the bolt is approximately equal to the sum of the initial tension and the external load. On the other hand, if the bolt is very yielding as compared with the connected members, then the resultant load will be either the initial tension or external load whichever is greater.

In order to determine the resultant axial load (P) on the bolt, the following equation may be used:

$$P = P_1 + \frac{a}{1+a} \times P_2 = P_1 + K\,P_2 \qquad \left(\text{Substituting } \frac{a}{1+a} = K\right)$$

where a = Ratio of elasticity of connected parts to the elasticity of bolt.

For soft gaskets and large bolts, the value of a is high and the value of $\frac{a}{1+a}$ is approximately equal to unity, so that the resultant load is equal to the initial tenion and the external load.

For hard gaskets or metal to metal contact surfaces and with small bolts, the value of a is small and the resultant load is mainly due to the initial tension (or external load, in rare case it is greater than initial tension).

12.22 Bolts of Uniform Strength

When a bolt is subjected to shock loading, the resilience of the bolt should be considered in order to prevent breakage at the thread. In an ordinary bolt, the effect of the impulsive loads applied axially is concentrated on the weakest part of the bolt *i.e.* the cross-sectional area at the root of the threads. In other words, the stress in the threaded part of the bolt will be higher than that in the shank. Hence a great portion of the energy will be absorbed at the region of the threaded part which may fracture the threaded portion because of its small length.

If the shank of the bolt is turned down to a diameter equal or even slightly less than the core diameter of the thread, then the shank of the bolt will undergo a higher stress. This means that a shank will absorb a large portion of the energy, thus relieving the material at the sections near the thread. The bolt, in this way, becomes stronger and lighter and it increases the shock absorbing capacity of the bolt because of increased modulus of resilience. This gives us *bolts of uniform strength*. The resilience of a bolt may also be increased by increasing its length.

Another method of obtaining the bolts of uniform strength is to drill an axial hole through the head as far as the threaded portion such that the area of the shank becomes equal to the root area of the thread.

12.23 Cotter and Knuckle Joints

A cotter is a flat wedge shaped piece of rectangular cross-section and its width tapered. The taper varies from 1 in 48 to 1 in 24. A cotter joint is a temporary fastening and is used to connect rigidly two co-axial rods or bars which are subjected to axial tensile or compressive forces. It is usually used in connecting a piston rod to the cross-head of a reciprocating steam engine. The following three types of cotter joints are commonly used to connect two rods by a cotter:

1. Socket and spigot cotter joint, 2. Sleeve and cotter joint, and 3. Gib and cotter joint.

A knuckle joint is used to connect two rods which are under the action of tensile loads. However, if the joint is guided, the rods may support a compressive load. Its use is found in the link of a cycle chain, valve rod joint with eccentric rod, pump rod joint etc.

12.24 Keys and Coupling

A key is a piece of mild steel inserted between the shaft and hub or boss of the pulley to connect these together in order to prevent relative motion between them. It is always inserted parallel to the shaft. Keys are temporary fastenings and are subjected to considerable crushing and shearing stresses. The following are various types of keys:

1. Sunk keys; 2. Saddle keys; 3. Tangent keys; 4. Round keys; 5. Splines; and 6. Woodruff key.

The *sunk keys* may be rectangular sunk key, square sunk key, parallel sunk key, jib-head key and feather key.

The width of key is usually $d/4$ and thickness of key is $d/6$, where d is the diameter of shaft or diameter of the hole in the hub. The taper of a rectangular sunk key is 1 in 100 and it is given on the top side only

The *parallel sunk key* is a taperless key and may be rectangular or square in cross -section. It is used where the pulley, gear or other mating piece is required to slide along the shaft.

A *feather key* is a special type of parallel key which transmits a turning moment and also permits axial movement.

A *wood ruff key* is a piece from a cylindrical disc having segmental cross-section. It is capable of tilting in a recess milled out in the shaft by a cutter having the same curvature as the disc from which the key is made.

The *saddle keys* may be flat saddle key and hollow saddle key. A *flat saddle key* is a taper key which fits in a keyway in the hub and is flat on the shaft. A *hollow saddle key* is a taper key which fits in a keyway in the hub and the bottom of the key is shaped to fit the curved surface of the shaft.

The *tangent keys* are fitted in pair at right angles. Each key is to withstand torsion in one direction only.

Sometimes, keys are made integral with the shaft which fits in the keyways broached in the hub. Such shafts are known as *splined shafts*. These shafts usually have four, six, ten or sixteen splines.

In designing a key, the distribution of forces along the length of key is assumed uniform. Due to the power transmitted by the shaft, the key may fail due to shearing or crushing. The key will be equally strong in shearing and crushing, if

$$\frac{w}{t}=\frac{\sigma_c}{2\tau}$$

where w and t = Width and thickness of key.

The permissible crushing stress (σ_c) for the usual key material is atleast twice the permissible shearing stress (τ). Therefore from the above equation, we have $w = t$. In other words, a square key is equally strong in shearing and crushing.

When the key material is same as that of the shaft and the width of key is one-fourth the diameter of shaft (d), then length of key will be 1.571 d.

12.25 Shaft Coupling

Shafts are usually available upto 7 metres length due to inconvenience in transport. In order to have a greater length, it becomes necessary to join two or more pieces of the shaft by means of a coupling. A good shaft coupling should have the following requirements :

1. It should be easy to connect or disconnect.
2. In should transmit the full power from one shaft to the other shaft without losses.
3. In should hold the shaft in perfect alignment.
4. It should reduce the transmission of shock loads from one shaft to another shaft.
5. It should have no projecting parts.

The two main types of shaft couplings are as follows:

1. Rigid coupling, and 2. Flexible coupling.

The *rigid coupling* is used to connect two shafts which are perfectly aligned. The following types of rigid coupling are important:

(*a*) Sleeve or muff coupling;

(*b*) Clamp or split muff or compression coupling, and

(*c*) Flange coupling.

The *flexible coupling* is used to connect two shafts having both lateral and angular misalignment. The following types of flexible coupling are important:

(*a*) Bushed pin type coupling ;

(*b*) Universal coupling ; and

(*c*) Oldham coupling.

The above types of couplings are discussed, in brief, as follows:

Sleeve or Muff coupling. The sleeve or muff coupling is designed as a hollow shaft. The usual proportions of a cast iron sleeve coupling are as follows:

Outer diameter of the muff or sleeve = $2d + 13$ mm

and length of the muff or sleeve = $3.5\,d$

where d is the diameter of the shaft.

Clamp or Compression coupling. It is also known as *split-muff coupling*. In this case, the muff or sleeve is made into two halves and are bolted together. The number of bolts may be two, four or six. The proportion for the muff are same as discussed above.

Flange coupling. A flange coupling usually applies to a coupling having two separate cast iron flanges. The two flanges are coupled together by means of bolts and nuts. Generally, three, four or six bolts are used. The keys are staggered at right angle along the circumference of the shafts in order to divide the weakening effect caused by keyways. The usual proportions of a cast iron flange coupling are as follows:

If d is the diameter of the shaft or inner diameter of the hub, then

Outside diameter of hub = $2d$

Length of hub = $1.5\,d$

Pitch circle diameter of bolts = $3d$

Outside diameter of flange = $4d$

Thickness of flange = $0.5\,d$

Number of bolts = 3, for d upto 40 mm

= 4, for d upto 100 mm

= 6, for d upto 180 mm

Thickness of protective circumferential flange

= $0.25\,d$

In a marine type flange coupling, the flanges are forged integral with the shafts. The flanges are held together by means of tapered headless bolts, numbering from four to twelve depending upon the diameter of bolt. The number of bolts may be chosen from the following table:

Table. 12.1. Number of bolts for a marine type flange coupling.

[According to I S : 3653 – 1966 (Reaffirmed 1990)]

Shaft diameter (mm)	35 to 55	56 to 150	151 to 230	231 to 390	Above 390
No. of bolts	4	6	8	10	12

The other proportions for marine type flange coupling are

Thickness of flange = $d/3$

Taper of bolt = 1 in 20 to 1 in 40

Pitch circle diameter of bolts = $1.6\,d$

Outer diameter of flange = $2.2\,d$

Bushed-pin flexible coupling. It is a modification of the rigid type of flange coupling. The coupling bolts are known as pins. The rubber or leather bushes are used over the pins. The two halves of the coupling are dissimilar in construction. There is no rigid connection between them and the drive takes place through the medium of the compressible rubber or leather bushes.

Universal (or Hooke's) coupling. A universal or Hooke's coupling is used to connect two shafts whose axes intersect at a small angle. The inclination of the two shafts may be constant, but in actual practice, it varies when the motion is transmitted from one shaft to another. The main application of the universal or Hooke's coupling is found in the transmission from the gear box to the differential or back axle of the automobiles. A Hooke's coupling is also used for transmission of power to different spindles of multiple drilling machine. It is used as a knee joint in milling machines.

Oldham coupling. It is used to join two shafts which have lateral misalignment.

12.26 Shafts

A shaft is a rotating machine element which is used to transmit power from one place to another. The shafts are generally manufactured by hot rolling and finished to size by cold drawing or turning and grinding. The cold rolled shafts are stronger than hot rolled shafts, but with higher residual stresses.

The shaft may be a transmission shaft (such as counter shafts, line shafts, over head shafts etc.) or a machine shaft (such as crank shaft).

The standard sizes of transmission shaft are :

25 mm to 60 mm with 5 mm steps ; 60 mm to 110 mm with 10 mm steps ; 110 mm to 140 mm with 15 mm steps ; and 140 mm to 500 mm with 20 mm steps.

The standard length of the shafts are 5 m, 6 m and 7m.

The following stresses are induced in the shafts:

1. Shear stresses due to transmission of torque (*i.e.* due to torsional load).
2. Bending stresses (tensile or compressive) due to the forces acting upon machine elements like gears, pulleys etc. as well as due to the weight of the shaft itself.
3. Stresses due to combined torsional and bending loads.

When a shaft is subjected to a twisting moment (or torque) only then the diameter of the shaft may be obtained from the torsion equation, *i.e.*

$$T = \frac{\pi}{16} \times \tau \times d^3 \qquad \text{... (For a solid shaft)}$$

$$= \frac{\pi}{16} \times \tau \left[\frac{(d_o)^4 - (d_i)^4}{d_o}\right] \qquad \text{... (For a hollow shaft)}$$

where
T = Twisting moment (or torque) acting upon the shaft,
τ = Torsional shear stress,
d = Diameter of the solid shaft, and
d_o and d_i = Outside and inside diameter of the hollow shaft.

The hollow shafts are usually used in marine work. These shafts are stronger per kg of material. When a hollow shaft is to be made equal in strength to a solid shaft, then the twisting moment of both the shafts must be same.

When the shaft is subjected to a bending moment only, then the diameter of the shaft may be obtained from the bending equation, *i.e.*

$$M = \frac{\pi}{32} \times \sigma_b \times d^3 \qquad \text{... (For a solid shaft)}$$

$$= \frac{\pi}{32} \times \sigma_b \left[\frac{(d_o)^4 - (d_i)^4}{d_o}\right] \qquad \text{... (For a hollow shaft)}$$

where σ_b = Bending stress.

It may be noted that the axles are used to transmit bending moment only. Thus, axles are designed on the basis of bending moment only.

When a shaft is subjected to combined twisting moment and bending moment, then the shaft is designed on the basis of the following two theories.

(*a*) *Maximum shear stress theory or Guest's theory.* It is used for ductile materials such as mild steel.

(*b*) *Maximum normal stress theory or Rankine's theory.* It is used for brittle materials such as cast iron.

According to maximum shear stress theory, the maximum shear stress in the shaft,

$$\tau_{max} = \frac{1}{2}\sqrt{(\sigma_b)^2 + 4\tau^2} = \frac{16}{\pi d^3}\left[\sqrt{M^2 + T^2}\right]$$

where
$$\sigma_b = \frac{32\,M}{\pi d^3}\ ; \text{ and } \tau = \frac{16\,T}{\pi d^3}$$

The expression $\sqrt{M^2 + T^2}$ is known as *equivalent twisting moment.*

According to maximum normal stress theory, the maximum normal stress in the shaft,

$$\sigma_{b(max)} = \frac{1}{2}\sigma_b + \frac{1}{2}\sqrt{(\sigma_b)^2 + 4\tau} = \frac{32}{\pi d^3}\left[\frac{1}{2}\left(M + \sqrt{M^2 + T^2}\right)\right]$$

The expression $\left[\frac{1}{2}\left(M + \sqrt{M^2 + T^2}\right)\right]$ is known as *equivalent bending moment.*

12.27 Levers

A lever is a rigid rod or bar capable of turning about a fixed point called *fulcrum.* It is used as a machine to lift a load by the application of a small effort. The ratio of the load lifted to the effort applied is called *mechanical advantage.* The perpendicular distance between the load point and fulcrum is known as *load arm* and the perpendicular distance between the effort point and fulcrum is called *effort arm.* The ratio of the effort arm to the load arm is called leverage.

The levers may be of *first type, second type* and *third type.* In the first type of levers, the fulcrum is in between the load and effort. Since the effort arm is greater than load arm, therefore, the mechanical advantage is more than one. Such type of levers are commonly found in bell cranked levers used in railway signalling arrangement, rocker arm in internal combustion engines, handle of a hand pump, hand wheel of a punching press, beam of a balance, foot lever etc.

In the second type of levers, the load is in between the fulcrum and effort. In this case, the effort arm is more than load arm, therefore, the mechanical advantage is more than one. The application of such type of levers is found in levers of loaded safety valves.

In the third type of levers, the effort is in between the fulcrum and load. Since the effort arm, in this case, is less than the load arm, therefore, the mechanical advantage is less than one. A pair of tongs, the treadle of a sewing machine etc. are examples of this type of lever.

12.28 Columns and Struts

A machine part subjected to an axial compressive force is called a strut. A strut may be horizontal, inclined or even vertical. But a vertical strut is known as a column, pillar or stanchion.

The columns which have lengths less than 8 times their diameter are called *short columns* whereas the columns which have lengths more than 30 times their diameter are called *long columns*.

The load, at which the column tends to have lateral displacement or tends to buckle is called *buckling load, critical load* or *crippling load* and the column is said to have developed an elastic instability. The buckling takes place about the axis having minimum radius of gyration or least moment of inertia. It may be noted that for a long column, the value of buckling load will be less than the crushing load.

The following four types of end conditions are important for columns:

(*a*) Both ends hinged or pin jointed ; (*b*) Both ends fixed ; (*c*) One end fixed and other end hinged ; and (*d*) One end fixed and other end free.

According to Euler's theory, the crippling or buckling load (W_{cr}) under various end conditions is represented by a general equation,

$$W_{cr} = \frac{C\pi^2 EI}{l^2} = \frac{C\pi^2 E A k^2}{l^2} = \frac{C\pi^2 E A}{(l/k)^2} \qquad \ldots (\because I = Ak^2)$$

where
E = Modulus of elasticity or Young's modulus for the material of the column,
A = Area of cross-section,
k = Least radius of gyration of the cross-section,
l = Length of the column, and
C = Constant, representing the end conditions of the column or end fixity constant. Its value is 1 for both ends hinged, 4 for both ends fixed, 2 for one end fixed and other end hinged, 0.25 for one end fixed and other end free.

In the above Euler's formula, the ratio (l/k) is known as *slenderness ratio*. It may be defined as the ratio of the effective length of the column to the least radius of gyration of the section. If the slenderness ratio is less than 80, Euler's formula for a mild steel column is not valid. Sometimes, the columns whose slenderness ratio is more than 80, are known as long *columns* and those whose slenderness ratio is less than 80 are known as *short columns*. The Euler's formula holds good only for long columns. Rankine's formula gives a fairly correct result for all cases of columns, ranging from short to long columns. According to Rankine's formula,

$$\text{Crippling load,} \quad W_{cr} = \frac{\sigma_c \times A}{1 + a\left(\frac{L}{k}\right)^2}$$

where
σ_c = Crushing stress or yield stress in compression,
A = Cross-sectional area of the column,
a = Rankine's constant = $\frac{\sigma_c}{\pi^2 E}$,
L = Equivalent length of the column, and
k = Least radius of gyration.

In designing a connecting rod, Rankine's formula is used. A connecting rod subjected to an axial load W may buckle with X-axis as neutral axis (*i.e.* in the plane of motion of the connecting rod) or Y-axis as neutral axis (*i.e.* in the plane perpendicular to the plane of motion). The connecting rod is considered like both ends hinged for buckling about X-axis and both ends fixed for buckling about Y-axis. A connecting rod should be equally strong in buckling about either axes.

In order to have a connecting rod equally strong in buckling about X-axis and Y-axis, the moment of inertia about X-axis (I_{xx}) should be four times the moment of inertia about Y-axis (I_{yy}). In other words, the connecting rod is four times strong in buckling about Y-axis than about X-axis. If $I_{xx} > 4\,I_{yy}$, then buckling will occur about Y-axis and if $I_{xx} < 4\,I_{yy}$, buckling will occur about X-axis. In actual practice, I_{xx} is kept slightly less than $4\,I_{yy}$. It is usually taken between 3 and 3.5 and the connecting rod is designed for buckling about X-axis. The design will always be satisfactory for buckling about Y-axis. The most suitable section for the connecting rod is *I*-section.

12.29 Power Screws

The power screws (also known as translation screws) are used to convert rotary motion into translatory motion. Following are the three types of screw threads mostly used for power screws:

1. *Square thread.* It is adapted for transmission of power in either direction. This thread results in maximum efficiency and minimum radial or bursting pressure on the nut. The square threads are employed in screw jacks, presses and clamping devices.

2. *Acme or trapezoidal thread.* It is a modification of square thread. The slight slope given to its sides lowers the efficiency slightly than square thread and it also introduce some bursting pressure on the nut, but increases its area in shear.

3. *Buttress thread.* It is used when large forces act along the screw axis in one direction only. It has limited use for power transmission.

Notes: (*a*) The efficiency of a square threaded screw is maximum, if the helix angle (α) is equal to $(45° - \phi/2)$, where ϕ is the angle of friction.

(*b*) The maximum efficiency of a square threaded screw is given by

$$\eta_{max} = \frac{1 - \sin\phi}{1 + \sin\phi}$$

(*c*) A screw is said to be overhauling screw, if the friction angle (ϕ) is less than helix angle (α). The efficiency of overhauling screws is more than 50%.

(*d*) A screw is said to be self locking screw, if the friction angle is more than helix angle. The efficiency of self locking screws is less than 50%.

12.30 Flat Belt Drives

The belts or ropes are used to transmit power from one shaft to another by means of pulleys which rotate at the same speed or at different speeds. The amount of power transmitted depends upon the following factors :

1. The velocity of the belt.

2. The tension under which the belt is placed on the pulleys.
3. The arc of contact between the belt and the smaller pulley.
4. The conditions under which the belt is used.

The various types of belts used are flat belt, V-belt, circular belt or rope. The material used for belts and ropes must be strong, flexible and durable. It must have a high coefficient of friction. The belts, according to the material used, are classified as leather belts, cotton or fabric belts, rubber belts, and balata belts.

The coefficient of friction between the belt and the pulley depends upon the following factors: (*a*) The material of belt ; (*b*) The material of pulley ; (*c*) The slip of belt ;and (*d*) The speed of belt.

The power from one pulley to another pulley may be transmitted by any of the following types of belt drives :

1. *Open belt drive.* The open belt drive, is used with shafts arranged parallel and rotating in the same direction.

2. *Crossed or twist belt drive.* The crossed or twist belt drive, is used with shafts arranged parallel and rotating in the opposite directions.

3. *Quarter turn belt drive.* The quarter turn belt drive (also known as *right angle belt drive*), is used with shafts arranged at right angles and rotating in one definite direction.

4. *Belt drive with idler pulley.* A belt drive with an idler pulley (also known as *jockey pulley drive*) is used with shafts arranged parallel and when an open belt drive can not be used due to small angle of contact on the smaller pulley.

5. *Compound belt drive.* A compound belt drive is used when power is transmitted from one shaft to another through a number of pulleys.

6. *Stepped or cone pulley drive.* A stepped or cone pulley drive is used for changing the speed of the driven shaft while the main or driving shaft runs at constant speed.

7. *Fast and loose pulley drive.* A fast and loose pulley drive is used when the driven or machine shaft is to be started or stopped whenever desired without interfering with the driving shaft.

Sometimes the frictional grip between the belts and pulleys becomes insufficient and may cause some forward motion of the driver without carrying the belt with it. This is called *slip of the belt* and is generally expressed as a percentage. This results in the reduction of velocity ratio of the system.

When the belt passes from the slack side to the tight side, a certain portion of the belt extends and it contracts again when the belt passes from the tight side to the slack side. Due to these changes of length, there is a relative motion between the belt and the pulley surfaces. This relative motion is termed as *creep*. The total effect of creep is to reduce slightly the speed of the driven pulley or follower.

The power transmitted (P) by the belt is given by

$$P = (T_1 - T_2)\,v \quad \text{(in watts)}$$

where
T_1 = Tension in the belt on the tight side in newtons,
T_2 = Tension in the belt on the slack side in newtons,
v = Velocity of the belt in m / s.

The relation between the tight side and slack side tensions, in terms of coefficient of friction between the belt and pulley (μ) and the angle of contact (θ) is given by

$$\frac{T_1}{T_2} = e^{\mu\theta} \quad \text{or} \quad 2.3 \log\left(\frac{T_1}{T_2}\right) = \mu\theta$$

When the pulleys are made of the same material, the angle of contact (θ) at the smaller pulley is taken. It is given by

$$\theta = (180^\circ - 2\alpha)\frac{\pi}{180} \qquad \text{...(For open belt drive)}$$

$$= (180^\circ + 2\alpha)\frac{\pi}{180} \qquad \text{...(For crossed belt drive)}$$

where

$$\alpha = \sin^{-1}\left(\frac{r_1 - r_2}{x}\right) \qquad \text{...(For open belt drive)}$$

$$= \sin^{-1}\left(\frac{r_1 + r_2}{x}\right) \qquad \text{...(For crossed belt drive)}$$

When the pulleys are made of different material (*i.e.* when the coefficient of friction of the pulleys or the angle of contact are different), then the design will refer to the pulley for which $\mu.\theta$ is small.

Since the belt continuously runs over the pulleys, therefore, some centrifugal force is caused, whose effect is to increase the tension on both the tight as well as the slack sides. The tension caused by the centrifugal force is called *centrifugal tension*. Mathematically, centrifugal tension,

$$T_c = m.v^2 \quad \text{(in newtons)}$$

where
m = Mass of the belt per unit length in kg, and
v = Linear velocity of the belt in m / s.

The power transmitted by a belt drive is maximum, when the maximum tension is the belt (T) is three times the centrifugal tension (T_c). The velocity of the belt (v) for maximum power is given by

$$v = \sqrt{\frac{T}{3m}}$$

It may be noted that centrifugal tension has no effect on the power transmitted.

The motion of the belt (from the driver) and the follower (from the belt) is governed by a firm grip due to friction between the belt and the pulleys. In order to increase this grip, the belt is tightened up. At this stage, even when the pulleys are stationary, the belt is subjected to some tension, known as initial tension. Mathematically, initial tension,

$$T_o = \frac{T_1 + T_2 + 2T_c}{2} \qquad \text{...(Considering centrifugal tension)}$$

$$= \frac{T_1 + T_2}{2} \qquad \text{...(Neglecting centrifugal tension)}$$

12.31 V - belt and Rope Drives

A V-belt is mostly used in factories and workshops where a great amount of power is to be transmitted from one pulley to another when the two pulleys are very near to each other. The included angle for the V-belt is from 30° to 40°. The power is transmitted by the wedging action between the belt and the V-groove in the pulley or sheave. A clearance must be provided between the belt and the V-groove of the pulley in order to prevent* touching of the bottom as it becomes narrower from wear.

* The wire ropes make contact at bottom of the groove of the pulley.

In a multiple V-belt drive, all the belts should stretch at the same rate so that the load is equally divided between them. When one of the set of belts break, the entire set should be replaced at the same time. In case of V-belt and rope drive, the ratio of driving tensions (i.e. T_1 and T_2) is given by

$$2.3\log\left(\frac{T_1}{T_2}\right) = \mu.\theta.\operatorname{cosec}\beta$$

where β = Semi-groove angle of the pulley

The groove angle of the pulley for rope drive is usually 45°

12.32 Chain Drives

The chains are mostly used to transmit motion and power from one shaft to another, when the centre distance between their shafts is short. The chains may also be used for long centre distance of upto 8 metres. Since no slipping takes place during chain drive, therefore perfect velocity ratio is obtained.

The chains, on the basis of their use, are classified into the following three groups:

1. Hoisting and hauling (or crane) chains,
2. Conveyor (or tractive) chains, and
3. Power transmitting (or driving) chains.

The power transmitting chains are of the following three types :

(a) Block or bush chain,

(b) Bush roller chain, and

(c) Silent chain.

12.33 Springs

A spring is defined as an elastic body, whose function is to distort when loaded and to recover its original shape when load is removed. The various important applications of springs are as follows:

1. To cushion, absorb or control energy due to either shock or vibrations as in car springs, railway buffers, aircraft landing gears, shock absorbers and vibration dampers.
2. To apply forces, as in brakes, clutches, and spring loaded valves.
3. To control motion by maintaining contact between two elements as in cams and followers.
4. To measure forces, as in spring balances and engine indicators.
5. To store energy, as in watches, toys etc.

Though there are many types of the springs, yet the following, according to their shape, are important:

(a) *Helical springs.* The helical springs are made up of a wire coiled in the form of a helix and is primarily intended for compressive or tensile loads. The two forms of helical springs are *compression helical spring* and *tension helical spring*. The helical springs may be *closely coiled helical spring* and *open coiled helical spring*. The major stresses produced in helical springs are shear stresses due to twisting.

(b) *Conical and volute springs.* The conical and volute springs are used in special applications where a telescoping spring or a spring with a spring rate that increases with the load, is desired.

(c) *Torsion springs.* These springs may be helical or spiral type. The major stresses produced in torsion springs are tensile and compressive due to bending.

(d) *Laminated or leaf springs.* The laminated or leaf spring (also known as *flat spring* or

carriage spring) consists of a number of flat plates (known as leaves) of varying lengths held together by means of clamps and bolts. These are mostly used in automobiles.

(e) *Disc or bellevile springs.* These springs consist of a number of conical discs held together against slipping by a central bolt or tube.

The following terms used in connection with compression springs are important:

1. *Solid length.* It is the product of total number of coils (n') and the diameter of wire (d).
2. *Free length.* It is equal to the solid length plus the maximum deflection or the compression of the spring and the clearance between the adjacent coils (when fully compressed).
3. *Spring index.* It is defined as the ratio of the mean diameter of the coil (D) to the diameter of the wire (d).
4. *Spring rate.* It is defined as the load required per unit deflection of the spring. It is also called stiffness or spring constant.
5. *Pitch.* It is defined as the axial distance between adjacent coils in uncompressed state.

Consider an open coiled helical compression spring subjected to an axial load (W) as shown in Fig. 12.7. The maximum shear stress induced in the wire is given by

$$\tau = K\times\frac{8W.D}{\pi d^3} = K\times\frac{8W.C}{\pi d^2}$$

and compression produced in the spring.

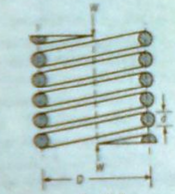


Fig. 12.7

$$\delta = \frac{8WD^3n}{Gd^4} = \frac{8WC^3n}{G.d}$$

where K = Wahl's stress factor

$$= \frac{4C-1}{4C-4}+\frac{0.615}{C}$$

C = Spring index $= D/d$,

n = Number of active coils, and

G = Modulus of rigidity for the material of the spring wire.

For springs made of rectangular wire, as shown in Fig. 12.8, the maximum shear stress is given by

$$\tau = K\times\frac{W.D(1.5t+0.9b)}{b^2t^2}$$

This expression is applicable when the longer side (i.e. $t > b$) parallel to the axis of the spring. But when the shorter side (i.e. $t < b$) parallel to the axis of the spring, then maximum shear stress,

$$\tau = K\times\frac{W.D(1.5b+0.9t)}{b^2t^2}$$

and deflection of the spring,

$$\delta = \frac{2.45\,W.D^3.n}{G.b^3(t-0.56b)}$$

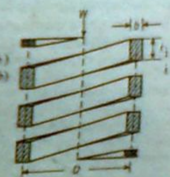


Fig. 12.8

For springs made of square wire, the dimensions b and t are equal.

12.34 Brakes

A brake is a device by means of which artificial frictional resistance is applied to a moving machine member, in order to retard or stop the motion of a machine. A shoe brake is commonly used on railway trains and tram cars. An internal expanding brake is commonly used in motor cars. For a shoe brake, the equivalent coefficient of friction (μ') is given by

$$\mu' = \frac{4\mu \sin\theta}{2\theta + \sin 2\theta}$$

where μ = Actual coefficient of friction, and

2θ = Angle of contact surface of the shoe.

In a band and block brake, the ratio of tensions on the tight and slack sides of the band is given by

$$\frac{T_1}{T_2} = \left[\frac{1+\mu\tan\theta}{1-\mu\tan\theta}\right]^n$$

where μ = Coefficient of friction between the blocks and the drum,

θ = Semi-angle of each block subtending at the centre of drum,

n = Number of blocks.

12.35 Sliding Contact Bearings

A bearing is a machine element which support another moving machine element (known as journal). It permits a relative motion between the contact surfaces of the members, while carrying the load. The bearings may be classified as follows:

1. *Radial bearings.* In radial bearings, the load acts perpendicular to the direction of motion of the moving element.

2. *Thrust bearings.* In thrust bearings, the load acts along the axis of rotation.

3. *Sliding contact bearings.* In sliding contact bearings, the sliding takes place along the surfaces of contact between the moving element and the fixed element. These are also known as *plain bearings*.

4. *Rolling contact bearings.* In rolling contact bearings, the steel balls or rollers are interposed between the moving and fixed element.

The sliding contact bearings in which the sliding action is along the circumference of a circle or an arc of a circle and carrying radial loads are known as *journal* or *sleeve bearings*. When the angle of contact of the bearing with the journal is 360°, then the bearing is called a *full journal bearing*. This type of bearing is commonly used in industrial machinery to accomodate bearing loads in any radial direction. When the angle of contact of the bearing with the journal is 120°, then the bearing is said to be *partial journal bearing*. This type of bearing has less friction than full journal bearing, but it can be used only where the load is always in one direction. The most common application of the partial journal bearings is found is rail road car axles. The full and partial journal bearings may be called as *clearance bearings*, because the diameter of the journal is less than that of the bearing. When a partial journal bearing has no clearance *i.e.* the diameters of the journal and bearing are equal, then the bearing is called a *fitted bearing*.

The sliding contact bearings, according to the thickness of layer of the lubricant between the bearing and the journal, may be also classified as follows:

1. *Thick film bearings.* The thick film bearings are those in which the working surfaces are completely separated from each other by the lubricant. Such type of bearings are also called as *hydrodynamic lubricated bearings*.

2. *Thin film bearings.* The thin film bearings are those in which, although lubricant is present, the working surfaces partially contact each other atleast part of the time. Such type of bearings are also called *boundary lubricated bearings*.

3. *Zero film bearings.* The zero film bearings are those which operate without any lubricant present.

4. *Hydrostatic or externally pressurized lubricated bearings.* The hydrostatic bearings are those which can support steady loads without any relative motion between the journal and the bearing. This is achieved by forcing externally pressurized lubricant between the members.

12.36 Wedge Film Journal Bearings

The load carrying ability of a wedge film journal bearing results when the journal and / or the bearing rotates relative to the load. When the journal rotates slowly in the anticlockwise direction, it will move towards left of the bearing making metal to metal contact. When the journal rotates at high speed in the anticlockwise direction, it will move towards right of the bearing making no metal to metal contact.

12.37 Sliding Contact Bearing Materials and Their Properties

The materials commonly used for sliding contact bearings are babbit metal (tin base and lead base babbits), bronzes (gunmetal and phosphor bronzes), cast iron, silver, carbon graphite, rubber, wood and plastics. The following properties must be considered in selecting the best material.

1. *Compressive strength.* The bearing material should have high compressive strength to withstand the maximum bearing pressure so as to prevent extrusion or permanent deformation of the bearing.

2. *Fatigue strength.* The bearing material should have sufficient fatigue strength so that it can withstand repeated loads without developing surface fatigue cracks.

3. *Conformability.* It is the ability of a bearing material to accomodate shaft deflections and bearing inaccuracies by plastic deformation (or creep) without excessive wear and heating.

4. *Embeddability.* It is the ability of a bearing material to accommodate (or embed) small particles of dust, grit etc. without scoring the material of the journal.

5. *Bondability.* Many high capacity bearings are made by bonding one or more thin layers of a bearing material to a high strength steel shell. Thus, the strength of bond *i.e.* bondability is an important consideration in selecting bearing material.

6. *Corrosion resistance.* The bearing material should not corrode away under the action of lubricating oil.

7. *Thermal conductivity.* The bearing material should be of high thermal conductivity.

8. *Thermal expansion.* The bearing material should be of low coefficient of thermal expansion.

12.38 Terms used in Hydrodynamic Journal Bearing

A hydrodynamic journal bearing is shown in Fig. 12.9, in which O is the centre of journal and O' is the centre of the bearing.

Let D = Diameter of the bearing,

d = Diameter of the journal, and

l = Length of the bearing.

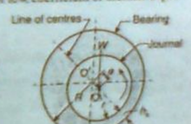


Fig. 12.9

The following terms used in hydrodynamic journal bearing are important :

1. *Diametral clearance.* It is the difference between the diameters of bearing and the journal.

2. *Radial clearance.* It is the difference between the radii of the bearing and the journal.

3. *Diametral clearance ratio.* It is the ratio of the diametral clearance to the diameter of the journal.

4. *Eccentricity.* It is the radial distance between the centre (O) of the bearing and the displaced centre (O') of the bearing under load.

5. *Minimum oil film thickness.* It is the minimum distance between the bearing and the journal, under complete lubrication condition. It is denoted by h_0 and its value may be assumed as one-fourth of diametral clearance.

6. *Attitude or eccentricity ratio.* It is the ratio of the eccentricity to the radial clearance.

7. *Short and long bearings.* If the ratio of length to the diameter of the journal (*i.e.* l/d) is less than one, then the bearing is said to be *short bearing*. On the other hand, if l/d is greater than one, then the bearing is known as *long bearing*.

Notes : 1. When $l = d$, then the bearing is called *square bearing*.

2. The value of l/d may be taken as 1 to 2 for general industrial machinery.

3. In crank shaft bearings, the ratio of l/d is frequently less than one.

12.39 Bearing Characteristic Number

It has been shown by experiments that the coefficient of friction (μ) for a full lubricated journal bearing is a function of three variables, *i.e.*, $\frac{ZN}{p}$, $\frac{d}{c}$ and $\frac{l}{d}$. Therefore, the coefficient of friction may be expressed as

$$\mu = \phi\left[\frac{ZN}{p}, \frac{d}{c}, \frac{l}{d}\right]$$

where ϕ = A functional relationship,

Z = Absolute viscosity of the lubricant in kg / m-s,

N = Speed of the journal in r.p.m.,

p = Bearing pressure on the projected bearing area in N / mm² $= W / l.d$,

W = Load on the journal,

d = Diameter of the journal,

l = Length of the bearing, and

c = Diametral clearance.

The factor ZN/p is termed as *bearing characteristic number* and is a dimensionless number.

Notes : 1. The Sommerfeld number is also a dimensionless parameter used extensively in the design of journal bearings. Mathematically,

$$\text{Sommerfeld number} = \frac{ZN}{p}\left(\frac{d}{c}\right)^2$$

For design purposes, its value is taken as 14.3×10^6, when Z is in kg / m – s and p is in N / mm².

2. The pressure at which the oil film breaks down so that metal to metal contact begins, is known as *critical pressure* or the *minimum operating pressure* of the bearing.

12.40 Heat Generated in a Bearing

The heat generated in a bearing is given by

$$Q_g = \mu W V \text{ N-m / s or J / s or watts}$$

where μ = Coefficient of friction,

W = Load on the bearing in newtons, and

V = Rubbing velocity in m / s.

The heat dissipated by the bearing is given by

$$Q_d = C.A\,(t_b - t_a) \text{ J / s or watts}$$

where C = Heat dissipation coefficient in W / m² / °C,

A = Projected area of the bearing in m²,

t_b = Temperature of bearing surface in °C, and

t_a = Temperature of the surrounding air in °C.

The value of C for unventilated bearings is 140 to 420 W / m² / °C and for ventilated bearings, it is 490 to 1400 W / m² / °C.

12.41 Rolling Contact Bearings

In rolling contact bearings, the contact between the bearing surfaces is rolling. Due to the low friction offered by rolling contact bearings, these are called *antifriction bearings*. The rolling contact bearings have the following advantages and disadvantages over sliding contact bearings :

Advantages

1. Low starting and running friction except at very high speeds.
2. Ability to withstand momentary shock loads.
3. Accuracy of shaft alignment.
4. Low cost of maintenance, as no lubrication is required while in service.
5. Small overall dimensions and are easy to mount and erect.

Disadvantages

1. More noisy at high speeds.
2. Low resistance to shock loading.
3. More initial cost.
4. Design of bearing housing complicated.

The rolling contact bearings are of the following two types :

(*a*) Ball bearing, and (*b*) Roller bearing.

The *ball and roller bearings* consist of an inner race which is mounted on the shaft or journal and an outer race which is carried by the housing or casing. In between the inner and outer race, there are balls or rollers. A number of balls or rollers are used and these are held at proper distances by retainers so that they do not touch each other. The retainers are thin strips and is usually in two parts which are assembled after the balls have been properly spaced. The ball bearings are used for light loads and the roller bearings are used for heavier loads.

The dimensions of ball bearings that have been standardised on an international basis are shown in Fig. 12.10. The bearings are designated by a number. In general, the number consists of at least three digits. Additional digits or letters are used to indicate special features. The last three digits give the series and the bore of the bearing. The last two digits from 04 onwards, when multiplied by 5, give the bore diameter in millimetres. The third from the last digit designates the series of the bearing. The most common ball bearings are available in four series as follows:

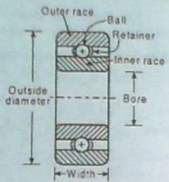


Fig. 12.10

1. Extra light (100), 2. Light (200), 3. Medium (300), and 4. Heavy (400).

Notes: (*a*) If a bearing is designated by a number 305, it means that the bearing is of medium series whose bore is 05 × 5 *i.e.* 25 mm.

(*b*) The extra light and light series are used where the loads are moderate and shaft sizes are comparatively large and also where available space is limited.

(*c*) The medium series has a capacity 30 to 40 percent over the light series.

(*d*) The heavy series has 20 to 30 percent capacity over the medium series. This series is not used extensively in industrial application.

12.42 Spur Gears

The motion and power transmitted by gears is kinematically equivalent to that transmitted by friction wheels or discs. A friction wheel with teeth cut on it is known as gear or toothed wheel.

When two parallel and coplaner shafts are connected by gears having teeth parallel to the axis of the shaft (called spur gears), the arrangement is known as *spur gearing*.

Another name given to the spur gearing is *helical gearing* in which the teeth are inclined to the axis of the shaft. There are single and double helical gears. The double helical gears are known as *herringbone gears*.

When two non-parallel or intersecting, but coplaner shafts are connected by gears, the arrangement is known as *bevel gearing* and the gears are called *bevel gears*. The bevel gears, like spur gears, may also have their teeth inclined to the face of the wheel, in which case they are known as *helical bevel gears*.

When two non-intersecting and non-parallel *i.e.* non-coplaner shafts are connected by gears, the arrangement is known as *skew bevel gearing* or *spiral gearing* and the gears are called *skew bevel gears* or *spiral gears*.

The various terms used in gears are shown in Fig. 12.11. These are discussed as follows:

1. *Pitch circle.* It is an imaginary circle which by pure rolling action, would give the same motion as the actual gear.

2. *Pitch circle diameter.* It is the diameter of the pitch circle. The size of the gear is usually specified by the pitch circle diameter. It is also called as *pitch diameter.*

3. *Pitch point.* It is a common point of contact between two pitch circles.

4. *Pitch surface.* It is the surface of the rolling discs which the meshing gears have replaced at the pitch circle.

5. *Pressure angle or angle of obliquity.* It is the angle between the common normal to two gear teeth at the point of contact and the common tangent at the pitch point. It is usually denoted by ϕ. The standard pressure angles are 14 ½° and 20°.

6. *Addendum.* It is the radial distance of a tooth from the pitch circle to the top of the tooth.

7. *Dedendum.* It is the radial distance of a tooth from the pitch circle to the bottom of the tooth.

8. *Addendum circle.* It is the circle drawn through the top of the teeth and is concentric with the pitch circle.

9. *Dedendum circle.* It is the circle drawn through the bottom of the teeth. It is also called root circle.

Note : Root circle diameter = Pitch circle diameter × cos ϕ, where ϕ is the pressure angle.

10. *Circular pitch.* It is the distance measured on the circumference of the pitch circle from a point of one tooth to the corresponding point on the next tooth. It is usually denoted by p_c. Mathematically,

Circular pitch, $p_c = \pi D/T$

where D = Diameter of the pitch circle, and

T = Number of teeth on the wheel.

A little consideration will show that the two gears will mesh together correctly, if the two wheels have the same circular pitch.

Note : If D_1 and D_2 are the diameters of the two meshing gears having the teeth T_1 and T_2 respectively, then for them to mesh correctly,

$$p_c = \frac{\pi D_1}{T_1} = \frac{\pi D_2}{T_2} \quad \text{or} \quad \frac{D_1}{D_2} = \frac{T_1}{T_2}$$

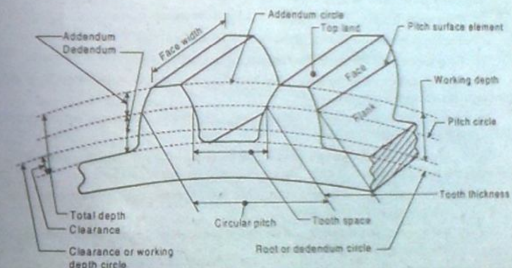


Fig. 12.11

11. *Diametral pitch.* It is the ratio of number of teeth to the pitch circle diameter in millimetres. It denoted by p_d. Mathematically,

Diametral pitch, $p_d = \dfrac{T}{D} = \dfrac{\pi}{p_c}$ $\left(\because p_c = \dfrac{\pi D}{T}\right)$

where T = Number of teeth, and

D = Pitch circle diameter.

12. *Module.* It is the ratio of the pitch circle diameter in millimetres to the number of teeth. It is

usually denoted by m. Mathematically,

$$\text{Module, } m = D/T$$

Note : The recommended series of modules in Indian Standard are 1, 1.25, 1.5, 2, 2.5, 3, 4, 5, 6, 8, 10, 12, 16, 20, 25, 32, 40 and 50.

The modules 1.125, 1.375, 1.75, 2.25, 2.75, 3.5, 4.5, 5.5, 7, 9, 11, 14, 18, 22, 28, 36 and 45 are of second choice.

13. *Clearance.* It is the radial distance from the top of the tooth to the bottom of the tooth, in a meshing gear. A circle passing through the top of the meshing gear is known as *clearance circle*.

14. *Total depth.* It is the radial distance between the addendum and the dedendum circle of a gear. It is equal to the sum of the addendum and dedendum.

15. *Working depth.* It is the radial distance from the addendum circle to the clearance circle. It is equal to the sum of the addendum of the two meshing gears.

16. *Tooth thickness.* It is the width of the tooth measured along the pitch circle.

17. *Tooth space.* It is the width of space between the two adjacent teeth measured along the pitch circle.

18. *Backlash.* It is the difference between the tooth space and the tooth thickness, as measured on the pitch circle.

19. *Face of the tooth.* It is surface of the tooth above the pitch surface.

20. *Top land.* It is the surface of the top of the tooth.

21. *Flank of the tooth.* It is the surface of the tooth below the pitch surface.

22. *Face width.* It is the width of the gear tooth measured parallel to its axis.

23. *Profile.* It is the curve formed by the face and flank of the tooth.

24. *Fillet radius.* It is the radius that connects the root circle to the profile of the tooth.

25. *Path of contact.* It is the path traced by the point of contact of two teeth from the beginning to the end of engagement.

26. *Length of the path of contact.* It is the length of the common normal cut-off by the addendum circles of the wheel and pinion.

27. *Arc of contact.* It is the path traced by a point on the pitch circle from the beginning to the end of engagement of a given pair of teeth. The arc of contact consists of two parts, *i.e.*

(*a*) *Arc of approach.* It is the portion of the path of contact from the beginning of the engagement to the pitch point.

(*b*) *Arc of recess.* It is the portion of the path of contact form the pitch point to the end of the engagement of a pair of teeth.

Note : The ratio of the length of arc of contact to the circular pitch is known as *contact ratio i.e.* number of pairs of teeth in contact.

12.43 Law of Gearing

According to law of gearing, the common normal at the point of contact between a pair of teeth must always pass through the pitch point.

12.44 Forms of Teeth

Following are the two types of teeth commonly used:

1. Cycloidal teeth, and 2. Involute teeth.

In actual practice, the involute gears are more commonly used as compared to cycloidal gears due to the following advantages:

(*a*) The most important advantage of the involute gears is that the* centre distance for a pair of involute gears can be varied within limits without changing the velocity ratio.

(*b*) In involute gears, the pressure angle from the start of the engagement of teeth to the end of engagement, remains constant. It is necessary for smooth running and less wear of gears.

(*c*) The involute teeth are easy to manufacture.

The only disadvantage of the involute teeth is that interference occurs with pinions having smaller number of teeth.

The phenomenon when the tip of a tooth undercuts the root on its mating gear is known as *interference*. The interference may only be prevented, if the addendum circles of the two mating gears cut the common tangent to the base circles between the points of tangency. The minimum number of teeth on the pinion which will mesh with any gear (also rack) without interference are given in the following table:

Table 12.2. Minimum number of teeth on the pinion in order to avoid interference.

S.No.	*Systems of gear teeth*	*Minimum number of teeth on the pinion*
1.	$14\frac{1}{2}°$ Composite	12
2.	$14\frac{1}{2}°$ Full depth involute	32
3.	20° Full depth involute	18
4.	20° Stub involute	14

12.45 Lewis Equation

The beam strength of gear teeth is determined from an equation (known as Lewis equation) and the load carrying ability of the toothed gears as determined by this equation gives satisfactory results. The tangential load (W_T) acting at the tooth (called the beam strength of the tooth) is given by

$$W_T = \sigma_w \cdot b \cdot p_c \cdot y$$

where
σ_w = Maximum bending stress or permissible working stress,
b = Width of gear face,
p_c = Circular pitch, and
y = Lewis form factor or tooth form factor

$= 0.124 - \dfrac{0.684}{T}$, for $14\frac{1}{2}°$ composite and full depth involute system

$= 0.154 - \dfrac{0.912}{T}$, for 20° full depth involute system

$= 0.175 - \dfrac{0.841}{T}$, for 20° stub system.

* The centre distance between the two meshing involute gears

$$= \frac{\text{Sum of base circle radii}}{\cos\phi}$$

where ϕ is the pressure angle.

The permissible working stress (σ_w) in the Lewis equation depends upon the material for which an *allowable static stress (σ_o) may be determined. The allowable static stress is the stress at the elastic limit of the material. It is also called the basic stress. According to Barth formula, the permissible working stress,

$$\sigma_w = \sigma_o \times C_v$$

where C_v = Velocity factor

$$= \frac{3}{3+v}, \text{ for ordinary cut gears operating at velocities up to } 12.5 \text{ m/s.}$$

$$= \frac{4.5}{4.5+v}, \text{ for carefully cut gears operating at velocities up to } 12.5 \text{ m/s}$$

$= \dfrac{6}{6+v}$, for very accurately cut and ground metallic gears operating at velocities upto 20 m/s.

$= \dfrac{0.75}{0.75+\sqrt{v}}$, for precision gears cut with high accuracy and operating at velocities upto 20 m/s.

$$= \left(\frac{0.75}{1+v}\right) + 0.25, \text{ for non-metallic gears.}$$

In the above expressions, v is the pitch line velocity in m / s.

In order to design spur gears, the following points may be noted:

1. The Lewis equation is applied only to the weaker of the two wheels (*i.e.* pinion or gear).
2. When both the pinion and the gear are made of the same material, then pinion is the weaker.
3. When the pinion and the gear are made of different materials, then the product of ($\sigma_w \times y$) or ($\sigma_o \times y$) is the deciding factor. The Lewis equation is used to that wheel for which ($\sigma_w \times y$) or ($\sigma_o \times y$) is less.
4. The product ($\sigma_w \times y$) is called *strength factor* of the gear.
5. The face width (b) may be taken as $3\,p_c$ to $4\,p_c$ (or $9.5\,m$ to $12.5\,m$) for cut teeth and $2\,p_c$ to $3\,p_c$ (or $6.5\,m$ to $9.5\,m$) for cast teeth.

12.46 Dynamic, Static and Wear Tooth Load

The dynamic tooth load is due to the following reasons:

1. Inaccuracies of tooth spacing,
2. Irregularities in tooth profiles, and
3. Deflections of teeth under load.

The static tooth load (also called beam strength or endurance strength of the tooth) is obtained by Lewis formula by substituting flexural endurance limit or elastic limit stress (σ_e) in place of permissible working stress (σ_w).

For safety, against tooth breakage, the static tooth load (W_S) should be greater than the dynamic load (W_D).

* The allowable static stress (σ_o) for steel gears is approximately one-third of the ultimate tensile strength.

The wear tooth load is the maximum load that a gear tooth can carry without premature wear. It depends upon the radii of curvature of the tooth profiles and on the elasticity and surface fatigue limits of the materials. The maximum wear load (W_w) must be greater than the dynamic load (W_D).

Note: For steel, the flexural endurance limit,

$$\sigma_e = 1.75 \times \text{Brinell hardness number } (B.H.N) \text{ (in MPa or N/mm}^2\text{)}$$

and surface endurance limit,

$$\sigma_{es} = (2.8 \times B.H.N - 70) \text{ MPa or N/mm}^2$$

12.47 Helical Gears

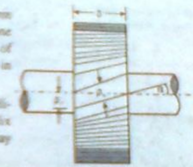


Fig. 12.12

A helical gear as shown in Fig. 12.12, has teeth in the form of helix around the gear. The helixes may be right handed on one gear and left handed on the other. The helical gears may be of single helical type or double helical type. The following terms in connection with helical gears are important:

1. *Helix angle.* It is a constant angle made by the helices with the axis of rotation. In single helical gears, the helix angle ranges from 20° to 35°, while for double helical gears, it may be made upto 45°.

2. *Axial pitch.* It is the distance, parallel to the axis, between similar faces of adjacent teeth. It is the same as circular pitch and is therefore denoted by p_c.

3. *Normal pitch.* It is the distance between similar faces of adjacent teeth along a helix on the pitch cylinders normal to the teeth. It is denoted by p_N.

Note: In single helical gears, the maximum face width (b) may be taken as $12.5\,m$ to $20\,m$, where m is the module. In terms of pinion diameter (D_p), the face width should be $1.5\,D_p$ to $2\,D_p$, although $2.5\,D_p$ may be used.

In case of double helical gears or herringbone gears, the minimum face width is given by

$$b = \frac{2.3\,p_c}{\tan\alpha} = \frac{2.3 \times \pi\, m}{\tan\alpha}$$

where α = Helix angle.

The maximum face width ranges from $20\,m$ to $30\,m$.

12.48 Bevel Gears

The bevel gears are used for transmitting power at a constant velocity ratio between two shafts whose axes intersect at a certain angle. The pitch surfaces for the bevel gear are frustums of cones.

The bevel gears may be classified into the following types, depending upon the angles between the shafts and the pitch surfaces.

1. *Miter gears.* When equal bevel gears (having equal teeth and equal pitch angles) connect two shafts whose axes intersect at right angle, then they are known as *miter gears*.

2. *Angular bevel gears.* When the bevel gears connect two shafts whose axes intersect at an angle other than a right angle, then they are known as *angular bevel gears*.

3. *Crown bevel gears.* When the bevel gears connect two shafts whose axes intersect at an angle greater than a right angle and one of the bevel gears has a pitch angle of 90°, then it is known as a *crown gear*.

4. *Internal bevel gears.* When the teeth on the bevel gear are out on the inside of the pitch cone, then they are known as *internal bevel gears.*

12.49 Worm Gears

The worm gears are widely used for transmitting power at high velocity ratios between non-intersecting shafts that are generally, but not necessarily, at right angles. It can give velocity ratios as high as 300 : 1 or more, but it has a lower efficiency.

The various terms used in connection with the worm gearing are as follows:

1. *Axial pitch.* It is also known as linear pitch of a worm. It is the distance measured axially (*i.e.* parallel to the axis of worm) from a point on one thread to the corresponding point on the adjacent thread on the worm.

2. *Lead.* It is the linear distance through which a point on a thread moves ahead in one revolution of the worm. For single start threads, lead is equal to axial pitch, but for multiple start threads, lead is equal to the product of axial pitch and number of starts.

3. *Lead angle.* It is the angle between the tangent to the thread helix on the pitch cylinder and the axis of the worm. It is denoted by λ.

The lead angle (λ) may vary from 9° to 45°. It has been shown by F.A. Halsey that a lead angle less than 9° results in rapid wear and the safe value of λ is $12\frac{1}{2}°$.

4. *Tooth pressure angle.* It is measured in a plane containing the axis of the worm and is equal to one-half the thread profile angle.

5. *Helix angle.* It is the angle between the tangent to the thread helix on the pitch cylinder and the axis of the worm. The worm helix angle (α_W) is the complement of worm lead angle (λ), *i.e.*

$$\alpha_W + \lambda = 90°$$

It may be noted that the helix angle on the worm is generally quite large and that on the worm gear is very small.

OBJECTIVE TYPE QUESTIONS

1. The elasticity is the property of a material which enables it to
   (*a*) regain its original shape after deformation when the external forces are removed
   (*b*) draw into wires by the application of a tensile force
   (*c*) resist fracture due to high impact loads
   (*d*) retain deformation produced under load permanently

2. The property of a material which enables it to be drawn into wires with the application of tensile force, is called
   (*a*) plasticity (*b*) elasticity (*c*) ductility (*d*) malleability

3. Which of the following material has the maximum ductility?
   (*a*) Mild steel (*b*) Copper (*c*) Zinc (*d*) Aluminium

4. The plasticity is the property of a material which enables it to
   (*a*) regain its original shape after deformation when the external forces are removed
   (*b*) draw into wires by the application of a tensile force
   (*c*) resist fracture due to high impact loads
   (*d*) retain deformation produced under load permanently

5. The property of a material which enables it to resist fracture due to high impact loads, is called toughness.
   (*a*) True (*b*) False

6. Which of the following property is desirable in parts subjected to shock and impact loads?
   (*a*) Strength (*b*) Stiffness (*c*) Brittleness (*d*) Toughness

7. A special case of ductility which permits materials to be rolled or hammered into thin sheets, is called
   (*a*) plasticity (*b*) elasticity (*c*) ductility (*d*) malleability

8. The toughness of a material.............. when it is heated.
   (*a*) increases (*b*) decreases (*c*) does not change

9. Which of the following property is essential for spring materials?
   (*a*) Stiffness (*b*) Ductility (*c*) Resilience (*d*) Plasticity

10. The malleable material should be plastic but is not essential to be so strong.
    (*a*) Agree (*b*) Disagree

11. The material commonly used for machine tool bodies is
    (*a*) mild steel (*b*) aluminium (*c*) brass (*d*) cast iron

12. When carbon in the cast iron is principally in the form of graphite, the cast iron will be of
    (*a*) grey colour (*b*) white colour (*c*) yellow colour (*d*) brown colour

13. When carbon in the cast iron is in the form of cementite, the cast iron will be of white colour.
    (*a*) Correct (*b*) Incorrect

14. According to Indian standard specifications, a grey cast iron designated by 'FG 200' means that the
    (*a*) carbon content is 2%
    (*b*) maximum compressive strength is 200 N/mm^2
    (*c*) minimum tensile strength is 200 N/mm^2
    (*d*) maximum shear strength is 200 N/mm^2

15. The material commonly used for crane hooks is
    (*a*) cast iron (*b*) wrought iron (*c*) mild steel (*d*) aluminium

16. A steel containing upto 0.15% carbon is known as
    (*a*) mild steel (*b*) dead mild steel
    (*c*) medium carbon steel (*d*) high carbon steel

17. According to Indian standard specifications, a plain carbon steel designated by 40C8 contains carbon
    (*a*) 0.20 to 0.40% (*b*) 0.35 to 0.45% (*c*) 0.40 to 0.60% (*d*) none of these

18. The shock resistance of steel is increased by adding
    (*a*) nickel (*b*) chromium
    (*c*) nickel and chromium (*d*) cobalt and molybedenum

19. The steel widely used for motor car crankshafts is
    (*a*) nickel steel (*b*) chrome steel
    (*c*) nickel chrome steel (*d*) high speed steel

479. (a)	480. (b)	481. (d)	482. (d)	483. (d)	484. (d)
485. (d)	486. (d)	487. (d)	488. (d)	489. (d)	490. (d)
491. (c)	492. (b)	493. (a)	494. (d)	495. (b)	496. (c)
497. (b)	498. (a)	499. (d)	500. (b)	501. (c)	502. (b)
503. (b)	504. (b)	505. (a)	506. (a)	507. (b)	508. (c)
509. (b)	510. (c)	511. (c)	512. (a)	513. (a)	514. (d)
515. (a)	516. (d)	517. (b)	518. (a)	519. (a)	520. (b)
521. (a)	522. (c)	523. (d)	524. (b)	525. (c)	526. (a)
527. (a)	528. (a)	529. (c)	530. (a)	531. (d)	532. (c)
533. (a)	534. (a)	535. (c)	536. (b)	537. (b)	538. (d)
539. (a)	540. (a)	541. (b)	542. (d)	543. (d)	544. (b)
545. (a)	546. (c)	547. (c)	548. (b)	549. (a)	550. (b)
551. (c)	552. (a)	553. (a)	554. (b)	555. (a)	556. (d)
557. (b)	558. (b)	559. (c)	560. (d)	561. (b)	562. (a)
563. (a)	564. (c)	565. (b)			

13

Engineering Materials

13.1 Introduction

The knowledge of materials and their properties is of great importance for a design engineer. A design engineer must be familiar with the effects which the manufacturing processes and heat treatment have on the properties of the materials. The engineering materials are mainly classified as

1. Metals and their alloys, such as iron, steel, copper, aluminium etc.
2. Non-metals, such as glass, rubber, plastic etc.

The metals may further be classified as:

(a) Ferrous metals; and (b) Non-ferrous metals.

The *ferrous metals* are those which have the iron as their main constituent, such as cast iron, wrought iron and steel.

The non-ferrous metals are those which have a metal other than iron as their main constituent, such as copper, aluminium, brass, tin, zinc etc.

The important mechanical properties of metals are as follows:

1. *Strength.* It is the ability of a material to resist the externally applied forces without breaking or yielding.

2. *Stiffness.* It is the ability of a material to resist deformation under stress. The modulus of elasticity is the measure of stiffness.

3. *Elasticity.* It is the property of a material to regain its original shape after deformation when the external forces are removed. This property is desirable for materials used in tools and machines. It may be noted that steel is more elastic than rubber.

4. *Plasticity.* It is property of a material which retains the deformation produced under load permanently. This property of material is necessary for forgings, in stamping images on coins, and in ornamental work.

5. *Ductility.* It is property of a material enabling it to be drawn into wire with the application of a tensile force. A ductile material commonly used in engineering practice (in order of diminishing ductility) are mild steel, copper, aluminium, nickel, zinc, tin and lead.

6. ***Brittleness.*** It is the property of a material opposite to ductility. It is the property of breaking of a material with little permanent distortion. Cast iron is a brittle material.

7. ***Malleability.*** It is a special case of ductility which permits materials to be rolled or hammered into thin sheets. A malleable material should be plastic but it is not essential to be so strong. The malleable materials commonly used in engineering practice (in order of diminishing malleability) are lead, soft steel, wrought iron, copper and aluminium.

8. ***Toughness.*** It is the property of a material to resist fracture due to high impact loads like hammer blows. The toughness of a material decreases when it is heated. This property is desirable in parts subjected to shock and impact loads.

9. ***Resilience.*** It is property of a material to absorb energy and to resist shock and impact

loads. It is measured by the amount of energy absorbed per unit volume within elastic limit. This property is essential for spring materials.

10. *Creep.* When a part is subjected to a constant stress at high temperature for a long period of time, it will undergo a slow and permanent deformation called *creep*. This property is considered in designing internal combustion engines, boilers and turbines.

11. *Fatigue.* When a material is subjected to repeated stresses, it fails at stresses below the yield point stresses. Such type of failure of a material is known as *fatigue*. The failure is caused by means of a progressive crack formation which are usually fine and microscopic size. This property is considered in designing shafts, connecting rods, springs, gears etc.

12. *Hardness.* It is a very important property of the metals and has a wide variety of meanings. It embraces many different properties such as resistance to wear, scratching, deformation and machinability etc. It also means the ability of a metal to cut another metal. The hardness is usually expressed in numbers which are dependent on the method of making the test.

13.2 Pig Iron

It is the crude form of iron and is used as a raw material for the production of various other ferrous metals, such as cast iron, wrought iron and steel. The pig iron is obtained by smelting iron ores in a blast furnace.

The iron ores are found in various forms as shown below:

Iron ore

As oxides
(*a*) Magnetite (Fe_3O_4)
(*b*) Haematite (Fe_2O_3)
(*c*) Limonite ($Fe_2O_3H_2O$)

As carbonates
Siderite ($FeCO_3$)

As sulphides
Pyrite (FeS_2)

The metallic contents of these iron ores are given in the following table:

Table 13.1. Metallic contents in iron ores.

Iron ore	*Colour*	*Iron content (%)*
Magnetite	Black	72
Haematite	Red	70
Limonite	Brown	60 – 65
Siderite	Brown	48

The haematite is widely used for the production of pig iron. Since pyrite contains only 30 to 40% iron, therefore it is not used for manufacturing pig iron.

The pig iron is obtained from the iron ores in the following steps:

1. *Concentration.* It is the process of removing the impurities like clay, sand etc. from the iron ore by washing with water.

2. *Calcination or roasting.* It is the process of expelling moisture, carbon dioxide, sulphur and arsenic from the iron ore by heating in shallow kilns.

3. *Smelting.* It is process of reducing the ore with carbon in the presence of a flux. The smelting is carried out in a large tower called *blast furnace*.

The blast furnace is a chimney like structure made of heavy steel plates lined inside with fire bricks to a thickness of 1.2 to 1.5 metres. It is about 30 metres high with a maximum internal diameter of 9 metres at its widest cross-section. The portion of the furnace above its widest cross-section is called *stack*. The top most portion of the stack is called *throat* through which the *charge is fed into the furnace. The portion of the furnace, below its widest cross-section, is known as *bosh* or the burning zone (or zone of fusion). The bosh is provided with holes for a number of water jacketed iron blowing pipes known as tuyers. The tuyers are 12 to 15 in number and are connected to bustle pipe surrounding the furnace.

In the lower part of the furnace (called zone of fusion), the temperature is 1200° C to 1300° C. In the middle part of the furnace (called zone of absorption), the temperature is 800° C to 1000° C. In the upper part of the furnace (called zone of reduction), the temperature is 400° C to 700° C.

At the bottom of the furnace, the molten iron sinks down while above this floats the fusible slage which protects the molten iron from oxidation. The molten iron thus produced is known as pig iron. The slag from the blast furnace consists of calcium, aluminium and ferrous silicates. It is used as a ballast for rail roads, mixed with tar for road making and in the cement manufacture.

The pig iron from the blast furnace contains 90 to 92% of iron. The various other elements present in pig iron are carbon (1 to 5%), silicon (1 to 2%), manganese (1 to 2%), sulphur and phosphorus (1 to 2%).

Note : Carbon plays an important role in iron. It exists in iron in two forms *i.e.* either in a free form (as graphite) or in a combined form (as cementite and pearlite). The presence of free carbon in iron imparts softness and a coarse crystalline structure to the metal, while the combined carbon makes the metal hard and gives a fine grained crystalline structure.

13.3 Cast Iron

The cast iron is obtained by remelting pig iron with coke and lime stone in a furnace known as cupola. It is primarily an alloy of iron and carbon. The carbon contents in cast iron varies from 1.7 to 4.5%. It may be present either as free carbon (or graphite) or combined carbon (or cementite).

Since the cast iron is a brittle material, therefore, it cannot be used in those parts which are subjected to shocks. The properties of cast iron which makes it a valuable material for engineering purposed are its low cost, good casting characteristics, high compressive strength, wear resistance and excellent machinability. The compressive strength of cast iron is much greater than tensile strength.

The cast iron also contains small amounts of impurities such as silicon, sulphur, manganese and phosphorus. The effect of these impurities on cast iron are as follows:

1. *Silicon.* It may be present in cast iron upto 4%. It provides the formation of free graphite which makes the iron soft and easily machinable.

2. *Sulphur.* It makes the cast iron hard and brittle. It must be kept well below 0.1% for most foundry purposes.

3. *Manganese.* It makes the cast iron white and hard. It is often kept below 0.75%.

4. *Phosphorus.* It aids fusibility and fluidity in cast iron, but induces brittleness. It is rarely allowed to exceed 1%.

The important types of cast iron are as follows:

(*a*) *Grey cast iron.* It is an ordinary commercial iron having 3 to 3.5% carbon. The grey colour

*The charge of the blast furnace consists of calcined ore (8 parts), coke (4 parts) and lime stone (1 part).

is due to the fact that carbon is present in the form of *free graphite. It has a low tensile strength, high compressive strength and no ductility. It can be easily machined.

According to Indian standards, grey cast iron is designated by the alphabets FG followed by a figure indicating the minimum tensile strength in MPa or N/mm^2. For example 'FG 150 means grey cast iron with 150 MPa or N/mm^2 as minimum tensile strength.

(*b*) *White cast iron.* It is a particular variety of cast iron having 1.75 to 2.3% carbon. The white colour is due to the fact that the carbon is in the form of carbide (known as cementite), which is the hardest constituent of iron. The white cast iron has a high tensile strength and a low compressive strength.

(*c*) *Chilled cast iron.* It is a white cast iron produced by quick cooling of molten iron. The quick cooling is generally called chilling and the iron so produced is known as chilled cast iron.

(*d*) *Mottled cast iron.* It is a product in between grey and white cast iron in composition, colour and general properties.

(*e*) *Malleable cast iron.* It is obtained from white cast iron by a suitable heat treatment process (*i.e.* annealing). According to Indian standard specifications, the malleable cast iron may be either whiteheart, blackheart or pearlitic and are designated by the alphabets WM, BM and PM respectively. These designations are followed by a figure indicating the minimum tensile strength in MPa or N/mm^2. For example 'WM350' denotes white heat malleable cast iron with 350 MPa as minimum tensile strength.

(*f*) ***Nodular or spheroidal graphite cast iron.*** It is also called ductile cast iron or high strength cast iron. This type of cast iron is obtained by adding small amounts of magnesium (0.1 to 0.8%) to the molten grey iron just after tapping. According to Indian standard specifications, the nodular or spheroidal graphite cast iron is designated by the alphabets 'SG' followed by the figures indicating the minimum tensile strength in MPa or N/mm^2 and the percentage elongation. For example, SG 400/15 means spheroidal graphite cast iron with 400 MPa as minimum tensile strength and 15 percent elongation.

(*g*) *Alloy cast iron.* It is produced by adding alloying elements like nickel, chromium, molybdenum, copper and vanadium in sufficient quantities. The alloy cast iron has special properties like increased strength, high wear resistance, corrosion resistance or heat resistance.

13.4 Wrought Iron

It is the purest iron which contains 99.5% iron but may contain upto 99.9% iron. The carbon content is about 0.02%. It is a tough, malleable and ductile material. It can not stand sudden and excessive shocks. It can be easily forged or welded.

13.5 Steel

It is an alloy of iron and carbon, with carbon content upto a maximum of 1.5%. Most of the steel produced now-a-days is ***plain carbon steel*** or simply ***carbon steel.*** It is divided into the following types depending upon the carbon content:

1. Dead mild steel — upto 0.15% Carbon
2. Low carbon or mild steel — 0.15% to 0.45% Carbon
3. Medium carbon steel — 0.45% to 0.8% Carbon
4. High carbon steel — 0.8% to 1.5% Carbon

According to Indian standards, the carbon steels are designated in the following order:

* When filing or machining cast iron makes our hands black, then it shows that free graphite is present in it.

(*a*) Figure indicating 100 times the average percentage of carbon content,

(*b*) Letter 'C', and

(*c*) Figure indicating 10 times the average percentage of manganese content. The figure after multiplying shall be rounded off to the nearest integer.

For example 20C 8 means carbon steel containing 0.15 to 0.25% (0.2% on an average) carbon and 0.60 to 0.90% (0.75% rounded off to 8% on an average) manganese.

The principal methods of manufacturing steel are as follows:

1. *Cementation process.* The steel made by this process is cement steel because ferrite in the wrought iron is converted into cementite (*i.e.*, iron carbide). Since carbon combines with wrought iron and has its surface covered with blisters, therefore, the steel produced by this process is known as ***blister steel.***

2. *Crucible process.* The steel produced by this method is very homogeneous, free from slag and dirt and much superior to cement steel. The steel so produced is known as *crucible steel.*

3. *Bessemer process.* In a bessemer process, following are the three distinctive stages used to convert molten pig iron to steel:

(*a*) In the first stage (known as *charging position*), the molten pig iron is poured into the converter.

(*b*) In the second stage (known as *blowing position*), the converter is tilted to the vertical position and the air blast turned on. In this stage, the silicon and manganese burns out which is indicated by the brown smoke rising up through the mouth of the converter. After this, the carbon is next to oxidise which is indicated by a white flame.

(*c*) In the third stage (known as *pouring position*), the white flame of the burning carbon drops and the contents of the converter are poured in a ladle. Now a small quantity of some alloy rich in carbon and manganese (*i.e.* spiegeleisen or ferro-manganese) is added to produce steel of quite good strength and ductility.

Note : The bessemer process may be *acidic* or *basic* depending upon the lining of furnace. In the *acidic bessemer process*, the furnace is lined with silica bricks. The slag produced in this process contains large amount of silica. Since phosphorus in a pig iron cannot be removed by this process, therefore acidic bessemer process is unsuitable for producing steel from pig iron containing large quantities of phosphorus.

In *basic bessemer process*, also known as *Thomas process*, the furnace is lined with a mixture of tar and burned dolomite. This process is applicable for making steel from pig iron which contains more than 1.5% phosphorus.

4. *Open hearth process.* The open hearth process of steel making is sometimes called 'Siemens-Martin Process'. This process is more suitable than Bessemer process when a large quantity of mild steel, with definite quality and composition, is required.

5. *Duplex process.* The duplex process of steel making is a combination of acidic bessemer process and basic open hearth process. This process is in operation at Tata Iron and Steel works, Jamshedpur (Bihar).

6. *L-D process* (*Linz-Donawitz process*). It is the latest development in steel making processes and is now adopted at Rourkela steel plant where three converters of 40 tonnes capacity are working.

7. *Electric process.* This process is mainly used for the preparation of high quality and special alloy steels of high melting point. The electric process may be acidic or basic, but basic process is mostly used because it permits extensive elimination of impurities. The basic lined furnace of the Heroult type is especially adopted to the production of best quality carbon and alloy steels

Note : The steel contains small amounts of impurities like silicon, sulphur, manganese and phosphorus. The effect of these impurities are as follows:

Silicon in the finished steel usually ranges from 0.05 to 0.30%. It is added in low carbon steels to prevent them from becoming porous. It removes the gases and oxides, prevent blow holes and thereby makes the steel tougher and harder.

Sulphur occurs in steel either as iron sulphide or manganese sulphide. Iron sulphide because of its low melting point produces red shortness whereas manganese sulphide does not effect so much.

Manganese serves as a valuable deoxidising and purifying agent, in steel. When used in ordinary low carbon steels, manganese makes the metal ductile and of good bending qualities. In high speed steels, it is used to tougher the metal and to increase its critical temperature.

Phosphorus makes the steel brittle. It also produces cold shortness in steel. In low carbon steels, it raises the yield point and improves the resistance to atmospheric corrosion. The sum of carbon and phosphorus usually does not exceed 0.25%.

13.6 Alloy Steel

An alloy steel may be defined as a steel to which elements other than carbon are added in sufficient amount to produce an improvement in properties. The chief alloying elements used in steel are as follows:

1. *Nickel.* The steels containing 2 to 5% nickel improves tensile strength, raises elastic limit, imparts hardness, toughness and reduces rust formation. It is largely used for boiler plates, automobile engine parts, large forgings, crankshafts, connecting rods etc. When 25% nickel is added to steel, it results in higher strength steels with improved shock and fatigue resistance. A nickel steel alloy containing about 36% nickel is known as *Invar*. It has nearly zero coefficient of expansion. So it is widely used for making pendulums of clocks, precision measuring instruments etc.

2. *Chromium.* The addition of chromium to steel increases strength, hardness and corrosion resistance. A chrome steel containing 0.5 to 2% chromium is used for balls, rollers and races for bearings, dies, permanent magnets etc. A steel containing 3.25% nickel, 1.5% chromium and 0.25% carbon is known as *nickel-chrome steel.* The combination of toughening effect of nickel and the hardening effect of chromium produces a steel of high tensile strength with great resistance to shock. It is extensively used for armour plates, motor car crankshafts, axles and gears etc.

3. *Vanadium.* It is added in low and medium carbon steels in order to increase their yield and tensile strength properties. In combination with chromium, it produces a marked effect on the properties of steel and makes the steel extremely tough and strong. These steels are largely used for making spring steels, high speed tool steels, crankshafts etc.

4. *Tungsten.* The addition of tungsten raises the critical temperature of steel and hence it is used in increasing the strength of the alloyed steels at high temperature. It imparts cutting hardness and abrasion resistance properties to steel. When added to the extent of 5 to 6%, it gives the steel good magnetic properties and as such it is commonly used for magnets, in electrical instruments etc. It is usually used in conjuction with other elements. Steel containing 18% tungsten, 4% chromium, 1% vanadium and 0.7% carbon is called as *tool steel* or *high speed steel.* Since the tools made with this steel have the ability to maintain its sharp cutting edge even at elevated temperature, therefore, it is used for making high speed cutting tools such as cutters, drills, dies, broaches, reamers etc.

5. *Manganese.* It is added to steel in order to reduce the formation of iron sulphide by combining with sulphur. It is usually added in the form of ferro-manganese or silico-mangenese. It makes the steel hard, tough and wear resisting.

Steel containing manganese varying from 10 to 14% and carbon from 1 to 1.3% form an alloy steel which is extensively hard and tough and a high resistance to abrasion. It is largely used for mining, rock crushing and railway equipment.

6. *Silicon.* It increases the strength and hardness of steel without lowering its ductility. Silicon steels containing from 1 to 2% silicon and 0.1 to 0.4% carbon have good magnetic permeability and high electrical resistance. It can withstand impact and fatigue even at elevated temperature. These steels are principally used for generators and transformers in the form of laminated cores.

7. *Cobalt.* It is added to high speed steel from 1 to 12%, to give red hardness by retention of hard carbides at high temperatures. It tends to decarburise steel during heat treatment. It increases hardness and strength but too much of it decreases impact resistance of steel. It also increases residual magnetism and coercive magnetic force in steel for magnets.

8. *Molybdenum.* A very small quantity (0.15 to 0.30%) of molybdenum is generally used with chromium and manganese (0.5 to 0.8%) to make molybdenum steel. These steels possess extra tensile strength and is used for air plane fuselage and automobile parts. It can replace tungsten in high speed steels.

13.7 Free Cutting Steel

The free cutting steels (sometimes known as free machining steels) contain sulphur and phosphorus. These steels have higher sulphur content than other carbon steels. These steels are used where rapid machining and high quality surface finish after machining is the prime requirement. It may be noted that free cutting steels have low dynamic strength and are more liable to corrosion. These steels are frequently supplied in the cold drawn form and have high tensile strength and hardness but less ductile when compared to ordinary carbon steels.

13.8 Stainless Steel

It is defined as that steel which when correctly heat treated and finished, resists oxidation and corrosive attack from most corrosive media. The different types of stainless steels are as follows:

1. *Martensitic stainless steel.* The chromium steels containing 12 to 14% chromium and 0.12 to 0.35% carbon is called martensitic stainless steel, as they possess martensitic structure. These steels are magnetic and may be hardened by suitable heat treatment and the hardness obtainable depends upon the carbon content. These steels can be easily welded and machined.

2. *Ferritic stainless steel.* The steels containing greater amount of chromium (from 16 to 18%) and about 0.12% carbon are called ferritic stainless steels. These steels have better corrosion resistant property than martensitic stainless steels.

3. *Austenitic stainless steel.* The steel containing high content of both chromium and nickel are called austenitic stainless steels. The most widely used steel contains 18% chromium and 8% nickel. Such a steel is commonly known as *18/8 steel.* These steels are non-magnetic and possesses greatest resistance to corrosion and good mechanical properties at elevated temperature.

13.9 Structure of Solids

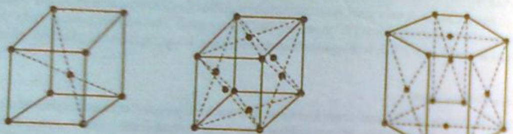
All solid substances are either amorphous solids or crystalline solids. In the *amorphous solids*, the atoms are arranged chaotically, *i.e.,* the atoms are not arranged in a systematic order. The common amorphous solids are wood, plastics, glass, paper, rubber etc. In *crystalline solids*, the atoms making up the crystals arrange themselves in a definite and orderly manner and form. All solid metals such as iron, copper, aluminium etc. are crystalline solids. The definite and orderly manner and form of atoms producing a geometrical shape in the aggregate is called *space lattice* or *crystal lattice.*

A crystal is composed of *unit cells.* A unit cell contains the smallest number of atoms, which when taken together have all the properties of the crystals of the particular metal. The unit cells are arranged like building blocks in a crystal, *i.e.* they have the same orientation and their similar faces are arranged like building blocks in a crystal, *i.e.* they have the same orientation and their similar faces are parallel. A unit cell may also be defined as the smallest parallelepiped which could be transposed in parallel.

three coordinate directions to build the space lattice. The space lattice of various substances differ in size and shape of their unit cells.

According to Bravais (a scientist), there are fourteen possible types of space lattices, but the following three types are usually found in most of the metals.

1. *Body centred cubic (B.C.C.) space lattice.* In a unit cell of body centred cubic space lattice, there are nine atoms. The eight atoms are located at the corners of the cube and one atom at its centre, as shown in Fig. 13.1 (*a*). This type of lattice is found in alpha (α)-iron, tungsten, chromium, manganese, molybdenum, tantalum, barium, vanadium etc.



(*a*) Body centred cubic (B.C.C.) space lattice.

(*b*) Face centred cubic (F.C.C.) space lattice.

(*c*) Close packed hexagonal (C.P.H.) space lattice.

Fig. 13.1

2. *Face centred cubic (F.C.C.) space lattice.* In a unit cell of face centred cubic space lattice, there are fourteen atoms. The eight atoms are located at the corner of the cube and six atoms at the centres of six faces, as shown in Fig. 13.1 (*b*). This type of lattice is found in gamma (γ) iron, aluminium, copper, lead, silver, nickel, gold, platinum, calcium etc.

3. *Close packed hexagonal (C.P.H.) space lattice.* In a unit cell of close packed hexagonal space lattice, there are seventeen atoms. The twelve atoms are located at the twelve corners of the hexagonal prism, one atom at the centre of each of the two hexagonal faces and three atoms are symmetrically arranged in the body of the cell as shown in Fig. 13.1 (*c*). This type of lattice is found in zinc, magnesium, cobalt, cadmium, antimony, bismuth, beryllium, titanium, zirconium etc.

13.10 Effect of Grain Size on Mechanical Properties

We have already discussed that all solid metals are crystalline and the crystals or grains are made up of several atoms. The grain size has an important effect on the mechanical properties of a metal. The size of the grains depends upon a number of factors, but the principal one is the heat treatment to which the metal has been subjected.

When a low carbon steel is heated, there is no change in grain size upto the **lower critical point* and it is same for all steels (723° C). At this temperature, birth of new grains take place. At the *upper critical point*, the average grain size is a minimum. Further heating of the steel causes an increase in the size of the grains, which in turn governs the final size of the grains when cooled. Some steels like medium carbon steel and many alloy steels when heated to a higher temperature, known as *coarsening temperature*, the grain size increases very rapidly. The coarsening temperature is not a fixed temperature and may be changed by prior hot or cold working and heat treatment.

The quenching of steel from the upper critical point results in a *fine grained structure*, whereas slow cooling or quenching from a higher temperature yields a *coarse grained structure*. The coarse

* The temperature point at which the change starts on heating is called lower *critical point* and the temperature point where this change ends in heating is called *upper critical point*. It varies according to the carbon content in steel.

grained steels are less tough and have greater tendency for distortion than those having a finegrain. A fine grained steel, in addition to being tougher, are more ductile and have less tendency to distort or crack during heat treatment.

13.11 Metallography

The study of internal structure of a metal or alloy, in relation to its physical and mechanical properties, under a microscope is called *metallography*.

When the structure of a metal is seen with the naked eye or by low power magnification, then it is said to be *macrography* and the observed structure is *macrostructure*. On the other hand, when the structure of the metal is seen at high magnification, then it is said to be *micrography* and the observed structure is called *microstructure*.

13.12 Allotropic Forms of Pure Iron

We know that pure substances may exist in more than one crystalline form. Each such crystalline form is stable over more or less well defined limits of temperature and pressure. This is known as *allotropy* or *polymorphism*. The pure iron exists in the following three allotropic forms:

(*a*) Alpha (α) iron which exists from the room temperature to 910° C. The α-iron is ferromagnetic at room temperature. It has a body centred cubic (B.C.C.) structure.

(*b*) Gamma (γ) iron which exists between 910° C to 1404° C. It has a face centred cubic (F.C.C.) structure.

(*c*) Delta (δ) iron which exists between 1404° C to 1539° C (melting point of pure iron). It has a body centred cubic (B.C.C.) structure but has longer cube edge than B.C.C. structure of α-iron.

13.13 Iron-Carbon Equilibrium Diagram

A modified iron-carbon diagram is shown in Fig. 13.2. The point *A* (1539° C) on the diagram is the melting point of pure iron. The point *E* shows the solubility limit of carbon in γ-iron at 1130° C (1.7%). The iron carbon alloys containing upto 1.7% carbon are called *steels* and those containing over 1.7% carbon are called *cast irons*. The iron carbon alloys containing 4.3% carbon are called *eutectic cast irons*, above 4.3% carbon are termed as *hyper-eutectic cast iron* and those in the range of 1.7 to 4.3% carbon are called *hypo-eutectic cast irons*.

We have already discussed that the temperature point at which the change starts on heating is called *lower critical point* and the temperature point where this change ends in heating is called *upper critical point*. The range between these two critical points is known as *critical range*. The temperature at which the change starts (*i.e.* lower critical point) is same for all steels (*i.e.* 723° C), but the ending point of transformation (*i.e.* upper critical point) varies according to the carbon content in steel. It will be seen that for a steel containing 0.8% carbon (wholly pearlite), there is only one critical point.

Notes : 1. The steels which contain less than 0.8% carbon are known as *hypo-eutectoid steels* which consists of ferrite and pearlite.

2. The steels which contain 0.8% carbon are known as *eutectoid steels* which consists entirely pearlite.

3. The steels which contain above 0.8% carbon are known as *hyper-eutectoid steels* which consists of cementite and pearlite.

4. Cementite consists of 93.33% iron and 6.67% carbon.

5. Pearlite consists of 87% ferrite and 13% cementite.

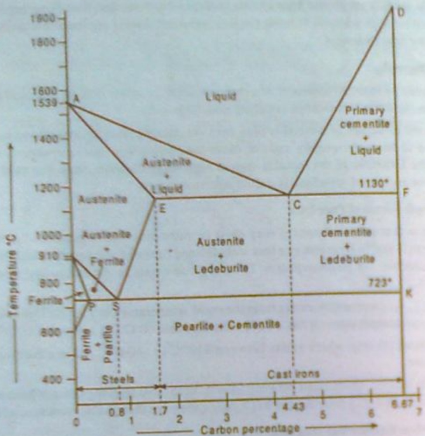


Fig. 13.2

13.14 Heat Treatment

The process of heat treatment is carried out first by heating the metal and then cooling it in the caustic soda solution, brine, water, oil or air. The purpose of heat treatment is to soften the metal, to change the grain size, to modify the structure of the material and to relieve the stresses set up in the material after hot or cold working. The various heat treatment processes commonly employed in engineering practice are as follows:

1. *Annealing*. It is one of the most important process of heat treatment of steel. Following are four types of annealing:

(*a*) *Full annealing*. The purpose of full annealing is to soften the metal, to refine the grain structure, to relieve the stresses and to remove trapped gases in the metal. The process consists of heating the steel 30° C - 50° C above the upper critical temperature for hypo-eutectoid steel and by the same temperature above the lower critical temperature for hyper-eutectoid steels. It is held at this temperature for sometime and then cooled slowly in the furnace.

(*b*) *Process annealing*. It is also known as low temperature annealing or sub-critical annealing. This process is used for relieving the internal stresses previously set up in the metal and for increasing th: machinability of the steel. In this process, steel is heated to a temperature below or close to the lower critical temperature (generally 550° C - 650° C), held at this temperature for sometime and then cooled slowly.

(*c*) *Spheroidise annealing* (*spheroidising*). It is usually applied to high carbon tool steels which are difficult to machine. The operation consists of heating the steel to a temperature slightly above the lower critical temperature (730° C to 770° C). It is held at this temperature for sometime and then cooled slowly to a temperature of 600° C. The spheroidising improves the machinability of steels, but lowers the hardness and tensile strength.

(*d*) *Diffusion annealing* (*Homogenization*). This process is mainly used for ingots and large castings. After diffusion annealing, the castings undergo full annealing to improve their properties or to refine grain structure. The process consists of heating the steel to a high temperature (1100° C – 1200° C). It is held at this temperature for 8 to 20 hours and then cooldded to 800° C – 850° C inside the furnace for a period of about 6 to 8 hours. It is further cooled in the air to room temperature.

2. *Normalising*. The normalising is done for the following purposes:

(*a*) To refine the grain structure of the steel to improve machinability, tensile strength and structure of weld.

(*b*) To remove strains caused by cold working processes.

(*c*) To remove dislocations caused in the internal structure of the steel due to hot working.

(*d*) To improve certain mechanical and electrical properties.

The process of normalising consists of heating the steel 30° C – 50° C above its upper critical temperature for hypo-eutectoid steels or Acm line for hyper-eutectoid steels. It is held at this temperature for about fifteen minutes and then allowed to cool down in still air. The process of normalising is frequently applied to castings and forgings etc.

3. *Hardening*. The main objects of hardening are

(*a*) To increase the hardness of the metal so that it can resist wear.

(*b*) To enable it to cut other metals, *i.e.* to make it suitable for cutting tools.

The process of hardening consists of heating the metal to a temperature of 30° C to 50° C above the upper critical point for hypo-eutect steels and by the same temperature above the lower critical temperature for hyper-eutectoid steels. It is held at this temperature for a considerable time and then quenched (cooled suddenly) in a suitable cooling medium.

4. *Austempering*. The austempering is misnomer because it is not a tempering process, but a hardening process. It is also known as *isothermal quenching*. In this process, the steel is heated, above the upper critical temperature, at about 875° C where the structure consists entirely of austenite. It is then suddenly cooled by quenching it in a salt bath or lead bath maintained at a temperature of about 250° C to 525° C.

5. *Martempering*. This process is also known as *stepped quenching* or *interrupted quenching*. It consists of heating steel above the upper critical point and then quenching it in a salt bath kept at a suitable temperature.

6. *Tempering*. The tempering (also known as drawing) is done for the following reasons:

(*a*) To reduce brittleness of the hardened steel and thus to increase ductility.

(*b*) To remove internal stresses caused by rapid cooling of steel.

(*c*) To make steel tough to resist shock and fatigue.

The tempering process consists of reheating the hardened steel to some temperature below the lower critical temperature, followed by any desired rate of cooling.

7. *Surface hardening* or *Case hardening*. In many engineering applications, it is desirable that a steel being used should have a hardened surface to resist wear and tear. At the sametime, it should have soft and tough interior or core so that it is able to absorb any shocks etc. This type of

treatment is applied to gears, ball bearings, railway wheels etc. The various surface or case hardening processes are as follows:

(a) Carburising ; (b) Cyaniding ; (c) Nitriding ; (d) Induction hardening ; and

(e) Flame hardening.

13.15 Non-ferrous Metals and Alloys

We have already discussed that the non-ferrous metals are those which contain a metal other than iron as their chief constituent. The various non-ferrous metals used in engineering practice are aluminium, copper, lead, tin, zinc, nickel etc. and their alloys. These non-ferrous metals and their alloys are discussed, in brief, as follows:

1. *Aluminium and its alloys.* The chief source of aluminium is a clayey mineral called *bauxite* which is a hydrated aluminium oxide. It is extensively used in air craft and automobile components where saving of weight is an advantage. The main aluminium alloys are as follows:

(a) *Duralumin.* The composition of this alloy is as follows:

Copper = 3.5 – 4.5% ; Manganese = 0.40 – 0.70% ; Magnesium = 0.40 – 0.70% ; and the remaining is aluminium.

This alloy possesses maximum strength (about 400 MPa) after heat treatment and age hardening. After working, if the metal is allowed to age for 3 or 4 days, it will be hardened. This phenomenon is known as *age hardening*.

(b) *Y-alloy.* It is also called *copper-aluminium alloy.* The composition of this alloy is as follows:

Copper = 3.5 – 4.5% ; Manganese = 1.2 – 1.7% ; Nickel = 1.8 – 2.3% ; silicon, magnesium, iron = 0.6% each ; and the remaining is aluminium.

This alloy is heat treated and age hardened like duralumin. It has better strength than duralumin at high temperature.

(c) *Magnalium.* It is made by melting the aluminium with 2 to 10% magnesium in a vacuum and then cooling it in a vacuum or under a pressure of 100 to 200 atmospheres. It also contains about 1.75% copper.

(d) *Hindalium.* It is an alloy of aluminium and magnesium with a small quantity of chromium. It is produced as a rolled product in 16 gauge, mainly for anodized utensil manufacture.

2. *Copper and its alloys.* The copper is one of the most widely used non-ferrous metal in industry. It is not found in pure state from under the earth. It occurs in some minerals such as copper glance, copper pyrites, malachite and azurite.

The copper alloys are broadly classified into the following two groups:

(a) Copper-zinc alloys (Brasses), in which zinc is the principal alloying metal, and

(b) Copper-tin alloys (Bronzes), in which tin is the principal alloying metal.

The most widely used copper-zinc alloy is brass. This is fundamentally a binary alloy of copper with zinc each 50%. There are various types of brasses, depending upon the proportion of copper and zinc. Brasses are very resistant to atmospheric corrosion and can be easily soldered.

The alloys of copper and tin are usually termed as bronzes. The useful range of composition is 75 to 95% copper and 5 to 25% tin. In corrosion resistant properties, bronzes are superior to brasses. Some of the common types of bronzes are as follows:

(i) *Phosphor bronze.* When bronze contains phosphorus, it is called phosphor bronze. Phosphorus increases the strength, ductility and soundness of castings. It contains 87 – 90% copper, 9 – 10% tin and 0.1 – 0.3% phosphorus. The alloy possesses good wearing qualities and high elasticity. It is used for bearings, worm wheels, gears, nuts, linings. It is also suitable for making springs.

(ii) *Silicon bronze.* It contains 96% copper, 3% silicon and 1% manganese or zinc. It has good general corrosion resistance of copper combined with higher strength. It is widely used for boilers, tanks, stoves or where high strength and good corrosion resistance is required.

(iii) *Beryllium bronze.* It is a copper base alloy containing about 97.75% copper and 2.25% beryllium. It has high yield point, high fatigue limit and excellent cold and hot corrosion resistance. It is particularly suitable material for springs, heavy duty electrical switches, cams and bushings. It has a film forming and a soft lubricating property, which makes it more suitable as a bearing metal.

(iv) *Manganese bronze.* It contains 60% copper, 35% zinc and 5% manganese. This metal is high resistant to corrosion. Worm gears are frequently made from this bronze.

(v) *Aluminium bronze.* It is an alloy of copper and aluminium. The aluminium bronze with 6-8% aluminium has valuable cold working properties. The 6% aluminium alloy has a fine gold colour which is used for imitation jewellery and decorative purposes.

3. *Gun metal.* It is an alloy of copper, tin and zinc. It usually contains 88% copper, 10% tin and 2% zinc. This metal is also known as *Admirality gun metal.* The zinc is added to clean the metal and to increase its fluidity. It is extensively used for casting boiler fittings, bushes, bearings, glands etc.

4. *Babbit metal.* A tin base alloy containing 88% tin, 8% antimony and 4% copper is called babbit metal. It is a soft material with a low coefficient of friction and has little strength.

5. *Nickel base alloys.* The most important nickel base alloys are as follows:

(a) *Monel metal.* It is an important alloy of nickel and copper. It contains 68% nickel, 29% copper and 3% other constituents. It resembles nickel in appearance and is strong, ductile and tough. It is superior to brass and bronze in corrosion resisting properties.

(b) *K-alloy.* It consists of 3% aluminium and 0.5% titanium, in addition to the composition of monel metal. It has better mechanical properties than monel metal.

(c) *Inconel.* It consists of 80% nickel, 14% chromium and 6% iron. This alloy has excellent mechanical properties at ordinary and elevated temperatures. It is used for making springs which have to withstand high temperatures and are exposed to corrosive action.

(d) *Nichrome.* It consists of 65% nickel, 15% chromium and 20% iron. It is used in making electrical resistance wire for electric furnaces and heating elements.

(e) *Nimonic.* It consists of 80% nickel and 20% chromium. It is widely used in gas turbine engines.

13.16 High Temperature Alloys

The high temperature alloys are those alloys which can withstand temperature in excess of 1100° C. These alloys are used in components of nuclear plants, jet and rocket engines. Some of the high temperature alloys are as follows:

1. *Incoloy.* It is a nickel base alloy. It consists of 42% nickel ; 13% chromium ; 6% molybdenum ; 2.4% titanium ; 0.4% carbon and the remaining is iron.

2. *Hastelloy.* It is also a nickel base alloy. It consists of 45% nickel; 22% chromium ; 9% molybdenum ; 1.5% cobalt ; 0.5% tungsten ; 0.15% carbon and the remaining is iron.

3. *Vitallium*. The main constituent of this alloy is cobalt. It consists of 62% cobalt, 28% chromium ; 5.5% molybdemum ; 2.5% nickel ; 1.7% iron and 0.28% carbon.

Note : Inconel and Nimonic, as discussed above, are also high temperature alloys.

13.17 Metals for Nuclear Energy

The various metals for producing nuclear energy are used as raw materials for moderators, reflectors, fuel elements, fuel canning materials, control elements and pressure vessel materials. The important metals used for nuclear energy are uranium, thorium, plutonium, zirconium, beryllium and niobium.

13.18 Plastics

The plastics are synthetic materials which are moulded into shape under pressure with or without the application of heat. These can also be cast, rolled, extruded, laminated and machined. Following are the two types of plastics :

(*a*) Thermosetting plastics, and (*b*) Thermoplastic.

The *thermosetting plastics* are those which are formed into shape under heat and pressure and results in a permanently hard product. The heat first softens the material, but as additional heat and pressure is applied, it becomes hard by a chemical change known as phenol-formaldehyde (Bakelite), phenol-furfural (Durite), urea-formaldehyde (Plaskon) etc.

The *thermoplastic* materials do not become hard with the application of heat and pressure and no chemical change occurs. They remain soft at elevated temperatures until they are hardened by cooling. These can be remelted repeatedly by successive application of heat. Some of the common thermoplastics are cellulose nitrate (Celluloid), polythene, polyvinyl acetate, polyvinyl chloride (P.V.C.) etc.

OBJECTIVE TYPE QUESTIONS

1. The strength is the ability of a material to resist
   (*a*) deformation under stress
   (*b*) externally applied forces with breakdown or yielding
   (*c*) fracture due to high impact loads (*d*) none of these
2. The stiffness is the ability of a material to resist deformation under stress.
   (*a*) Ture (*b*) False
3. The ability of a material to resist fracture due to high impact loads, is called
   (*a*) strength (*b*) stiffness (*c*) toughness (*d*) brittleness
4. The property of a material which enables it to retain the deformation permanently, is called
   (*a*) brittleness (*b*) ductility (*c*) malleability (*d*) plasticity
5. The ductility is the property of a material due to which it
   (*a*) can be drawn into wires (*b*) breaks with little permanent distortion
   (*c*) can be rolled or hammered into thin sheets (*d*) can resist fracture due to high impact loads
6. The malleability is the property of a material due to which it can be rolled or hammered into thin sheets.
   (*a*) Agree (*b*) Disagree
7. Which of the following property is desirable for materials used in tools and machines?
   (*a*) Elasticity (*b*) Plasticity (*c*) Ductility (*d*) Malleability

8. The property of a material necessary for forgings, in stamping images on coins and in ornamental work, is
   (*a*) elasticity (*b*) plasticity (*c*) ductility (*d*) malleability
9. Which of the following property is desirable in parts subjected to shock and impact loads?
   (*a*) Strength (*b*) Stiffness (*c*) Brittleness (*d*) Toughness
10. The property of a material essential for spring materials is
    (*a*) stiffness (*b*) ductility (*c*) resilience (*d*) plasticity
11. The toughness of a material............when it is heated.
    (*a*) remains same (*b*) decreases (*c*) increases
12. Which of the following material has maximum ductility?
    (*a*) Mild steel (*b*) Copper (*c*) Nickel (*d*) Aluminium
13. Brittle materials when subjected to tensile loads, snap off without giving any sensible elongation.
    (*a*) Yes (*b*) No
14. The property of a material due to which it breaks with little permanent distortion, is called
    (*a*) brittleness (*b*) ductility (*c*) malleability (*d*) plasticity
15. The hardness is the property of a material due to which it
    (*a*) can be drawn into wires (*b*) breaks with little permanent distortion
    (*c*) can cut another metal (*d*) can be rolled or hammered into thin sheets
16. Cast iron is a ductile material.
    (*a*) Right (*b*) Wrong
17. Which of the following material has maximum malleability?
    (*a*) Lead (*b*) Soft steel (*c*) Wrought iron (*d*) Copper
18. The ability of a material to absorb energy in the plastic range is called
    (*a*) resilience (*b*) creep (*c*) fatigue strength (*d*) toughness
19. The malleability is the property of a material by virtue of which a material
    (*a*) regains its shape and size after the removal of external forces
    (*b*) retains the deformation produced under load permanently
    (*c*) can be drawn into wires with the application of a tensile force
    (*d*) can be rolled or hammered into thin sheets
20. The ability of a material to undergo large permanent deformation with the application of a tensile force, is called ductility.
    (*a*) Correct (*b*) Incorrect
21. The stiffness is the ability of a material to resist
    (*a*) deformation under stress (*b*) fracture due to high impact loads
    (*c*) externally applied forces with breakdown or yielding
    (*d*) none of the above
22. Iron ore is, usually, found in the form of
    (*a*) oxides (*b*) carbonates (*c*) sulphides (*d*) all of these

14

Workshop Technology

14.1 Introduction

The subject of Workshop Technology has become increasingly important to the engineer, supervisor or worker engaged in the production of various types of machines or tools. The study of Workshop Technology has, therefore, been made compulsory these days for a worker, foreman and engineer so that he can make himself acquainted with basic knowledge of manufacturing processes and materials.

14.2 Mechanical Working of Metals

The mechanical working of metals is defined as an intentional deformation of metals plastically under the action of externally applied forces. It may be described as hot working and cold working depending upon whether the metal is worked above or below the recrystallisation temperature. The temperature at which the new grains are formed in the metal is known as *recrystallisation temperature*.

The metal is subjected to mechanical working for the following purposes:

(*a*) To reduce the original block or ingot into desired shapes,

(*b*) To refine grain size, and

(*c*) To control the direction of flow lines.

14.3 Hot Working

The working of metals above the recrystallisation temperature is called *hot working*. The hot working of metals has the following advantages and disadvantages:

Advantages

1. The porosity of the metal is largely eliminated, thus producing strong and uniform structure.
2. The grain structure of the metal is refined *i.e.* the coarse grains are converted into fine grains which change the properties of the metal.
3. The impurities like slag are squeezed into fibres and are uniformly distributed throughout the metal.
4. The mechanical properties such as toughness, ductility, percentage elongation, percentage reduction in area, and resistance to shock and vibration are improved due to the refinement of grains.
5. The deformation of the metal is easy, with a small pressure applied on it.

Disadvantages

1. It requires expensive tools.
2. It produces poor surface finish, due to the rapid oxidation and scale formation on the metal surface.
3. Due to the poor surface finish, close tolerances cannot be maintained.
4. The correct temperature range for working is difficult to maintain.

14.4 Hot Working Processes

The following are the various hot working processes:

1. *Hot rolling.* It is one of the most rapid method of converting large sections into desired shapes. The forming of bars, plates, sheets, rails, angles, I-beams and other structural sections are made by hot rolling.

The operation consists of passing the hot ingot through at least two rolls rotating in opposite directions at the same speed, as shown in Fig. 14.1. The space between the rolls is adjusted to conform to the desired thickness of the rolled section. The rolls, thus, squeeze the passing ingot to reduce its cross-section and increase its length.

The *ingots* are casted in moulds of suitable form and are used in rolling mills as raw material for preparing desired sections. The first operation to the ingot is carried out at the blooming mill where it is rolled to *blooms*. The bloom has a square cross-section with a minimum size of 150 mm × 150 mm. The blooms are cut up in lengths convenient for the subsequent reducing process into *billets*. The billet is smaller than a bloom and has a minimum size of 50 mm × 50 mm.

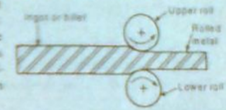


Fig. 14.1

The following types of rolling mills are used for rolling:

(*a*) *Two-high rolling mill.* It consists of two heavy rolls placed exactly one over the other. The metal piece is passed between the two rolls rotating at the same speed but in opposite direction.

(*b*) *Three-high rolling mill.* It consists of three rolls. The upper and bottom rolls rotate in the same direction while the middle roll rotates in the opposite direction.

(*c*) *Four-high rolling mill.* It consists of four rolls, two of which are working rolls and the other two are back-up rolls. The back-up rolls have larger diameter than working rolls.

2. *Hot forging.* It consists of heating the metal to plastic state and then the pressure is applied to form it into desired shapes and sizes. The pressure may be applied by hand hammers, power hammers or by forging machines.

3. *Hot spinning.* It consists of heating the metal to forging temperature and then forming it into the desired shape on a spinning lathe. The parts of circular cross-section which are symmetrical about the axis of rotation, are made by this process.

4. *Hot extrusion.* It consists of pressing a metal inside a chamber to force it out by high pressure through an orifice which is shaped to provide the desired form of the finished part. The rods, tubes, structural shapes, flooring strips and lead covered cables etc. are the typical products of extrusion.

5. *Hot drawing or cupping.* It is mostly used for the production of thick-walled seamless tubes and cylinders. It is usually performed in two stages. The first stage consists of drawing a cup out of a hot circular plate with the help of a die and punch. The second stage consists of reheating the drawn cup and drawing it further to the desired length having the required wall thickness.

6. *Hot piercing.* This process is used for the manufacture of seamless tubes. In its operation, the heated cylindrical billets of steel are passed between two conical shaped rolls operating in the same direction. A mandrel is provided between these rolls which assists in the piercing and controls the size of the hole as the billet is forced over it.

14.5 Cold Working

The working of metals below their recrystallisation temperature is known as *cold working*.

Most of the cold working processes are performed at room temperature. The cold working distorts the grain structure and does not provide an appreciable reduction in size. It requires much higher pressures than hot working. The extent to which a metal can be cold worked depends upon its ductility. The higher the ductility of the metal, the more it can be cold worked. It also increases tensile strength, yield strength and hardness of steel but lowers its ductility. The increase in hardness due to cold working is called *work-hardening*.

In general, cold working produces the following effects:

1. The stresses are set up in the metal which remain in the metal, unless they are removed by subsequent heat treatment.
2. A distortion of the grain structure is created.
3. The strength and hardness of the metal are increased with a corresponding loss in ductility.
4. The recrystalline temperature for steel is increased.
5. The surface finish is improved.
6. The close dimensional tolerance can be maintained.

14.6 Cold Working Processes

The following are the various cold working processes:

1. *Cold rolling.* It is generally employed for bars of all shapes, rods, sheets and strips, in order to provide a smooth and bright surface finish. It is also used to finish the hot rolled components to close tolerences and improve their toughness and hardness.

2. *Cold forging.* It is also called *swaging*. During this method of cold working, the metal is allowed to flow in some pre-determined shape according to design of dies, by a compressive force or impact. It is widely used in forming ductile metals. The commonly used cold forging processes are sizing, cold heading and rotary swaging.

The *sizing* is the operation of slightly compressing a forging, casting or steel assembly to obtain close tolerance and a flat surface.

The *cold heading* process is extensively used for making bolts, rivets and other similar headed parts.

The *rotary swaging* is used for reducing the diameters of round bars and tubes by rotating dies which open and close rapidly on the work.

3. *Cold spinning.* It is similar to hot spinning except that the metal is worked at room temperature. The process of cold spinning is best suited for aluminium and other soft metals. The commonly used spun articles out of aluminium and its alloys are processing kettles, cooking utensils, liquid containers and light reflectors etc.

4. *Cold extrusion.* It is similar to hot extrusion. The most common cold extrusion process is impact extrusion. The process of impact extrusion is limited to soft and ductile materials such as lead, tin, aluminium, zinc and some of their alloys. The various items of daily use such as tubes for shaving creams and tooth pastes and such other thin walled products are made by impact extrusion.

5. *Cold drawing.* It is generally employed for bars, rods, wires, tubes etc. The important cold working processes are bar drawing, wire drawing and tube drawing.

6. *Cold bending.* The bars, rods, wires, tubes, structural shapes and sheet metal may be bent to many shapes in cold conditions through dies.

7. *Cold or shot peening.* It is used to improve the fatigue resistance of the metal by setting

up compressive stresses in its surface. This is done by blasting or hurling a rain of small shot at high velocity against the surface to be peened.

14.7 Pattern Making

A pattern may be defined as a model or replica of desired casting which when moulded in sand forms an impression called mould. The mould when filled with molten metal forms casting after solidification of the poured metal. The quality and accuracy of casting depends upon the pattern making. The pattern may be made of wood, metal (Cast iron, Brass, Aluminium and its alloy, White metal), plaster, plastics and wax.

A pattern is always made larger than the required size of casting considering the various allowances. The following allowances are usually provided in a pattern:

1. *Shrinkage or contraction allowance.* The various metals used for casting contract after solidification in the mould. Since the contraction is different for different metals, therefore the corresponding allowances also differ. The following table shows the contraction allowances for castings of different materials in sand moulds.

Table 14.1. Shrinkage or contraction allowances.

Type of material	*Contraction allowance (mm / metre)*	*Type of material*	*Contraction allowance (mm / metre)*
Grey cast iron	7 to 10.5	Steel	20
White cast iron	21	Zinc and lead	24
Malleable iron	15	Bronze	10.5 to 21
Copper, brass and aluminium	16	Magnesium	18

Note: If a pattern is first made of wood and then from some other metal, then double allowances are provided on the wooden pattern. For example, if an aluminium pattern made from a wooden master pattern is to be used for grey iron castings, then a total shrinkage allowance of 26 mm / metre (16 mm / metre for aluminium and 10 mm / metre for grey iron), may be allowed on the pattern.

2. *Draft allowance.* It is a taper which is given to all the vertical walls of the pattern for easy and clean withdrawl of the pattern from the sand without damaging the mould cavity. It may be expressed in millimetres per metre on a side or in degrees. The amount of taper varies with the type of patterns. The wooden patterns require more taper than metal patterns because of the greater frictional resistance of the wooden surfaces.

3. *Finish or machining allowance.* This allowance is provided on the pattern if the casting is to be machined. This allowance is given in addition to shrinkage allowance. The amount of this allowance varies from 1.6 to 12.5 mm which depends upon the type of casting metal, size and shape of casting, method of casting used, method of machining to be employed and the degree of finish required. The ferrous metals require more machining allowance than nonferrous metals.

4. *Distortion or camber allowance.* This allowance is provided on patterns used for castings of such design in which the contraction is not uniform throughout.

5. *Rapping or shaking allowance.* This allowance is provided in the pattern to compensate for the rapping of mould because the pattern is to be rapped before removing it from the mould.

14.8 Types of Patterns

The common types of patterns are as follows:

(*a*) Solid or single piece pattern; (*b*) Split pattern (two piece or multipiece pattern); (*c*) Match plate pattern; (*d*) Cope and drag pattern; (*e*) Loose piece pattern; (*f*) Gated pattern; (*g*) Sweep pattern; (*h*) Skeleton pattern; (*i*) Shell pattern; (*j*) Segmental pattern; (*k*) Follow board pattern; (*l*) Lagged-up pattern; (*m*) Left and right hand pattern.

Note: When a pattern is made in three parts, the bottom part is known as *drag*, the top part is called *cope* while the middle one is called *cheek*.

14.9 Core Boxes

The core boxes, like patterns, may be made either of wood or metal. The core boxes are used for a casting requiring cores. Wood is generally used for making core boxes, but metal core boxes are preferred where cores are to be prepared in large numbers on mass production basis. Following are the various types of core boxes commonly used:

(*a*) Half core box ; (*b*) Dump core box ; (*c*) Split core box; (*d*) Strickle core box; (*e*) Right and left hand core box; (*f*) Loose piece core box ; (*g*) Gange core box.

The important parts of a pattern and core box are painted with different colours for the identification of their different parts.Though there is no universally accepted standard for colouring the surfaces, yet the following colour code is widely used :

1. The surface to be left unmachined are painted with *black* colour.
2. The surface to be machined are painted with *red* colour.
3. The core prints and seats for loose core prints are painted with *yellow* colour.
4. The seats for loose pieces are marked with red strips on yellow base.
5. The stop offs are indicated by diagonal black strips on yellow base.
6. The parting surface is indicated by no colour.

14.10 Foundry Tools and Equipments

The important foundry tools and equipments are discussed below:

1. *Hand tools*. The following hand tools are commonly employed in preparing the mould in foundry:

(*a*) *Shovel*. A shovel consists of a square pan fitted with a wooden handle. It is used for mixing and for moving the sand from one place to another in the foundry.

(*b*) *Riddle*. A riddle has a standard wire mesh fixed into a circular or square wooden frame. It is used for cleaning the moulding sand.

(*c*) *Rammer*. A *hand rammer* is made of wood or metal. It is a short rammer and is used for packing and ramming the sand for bench moulding. The *floor rammer* is similar in construction, but have long handles. It is used for floor moulding or for ramming large moulds. The *peen rammer* has a wedge shaped end and is used for setting into corners and pockets of the mould. The *pneumatic rammer* is an automatic rammer operated by compressed air. It is used in large moulds saving considerable labour and time.

(*d*) *Slick*. A slick is a double ended tool having a flat on one end and a spoon on the other. It is used for repairing and finishing the mould surfaces after the pattern is withdrawn.

(*e*) *Lifter*. A lifter is made of thin sections of steel of various width and lengths with one end bent at right angles. It is used for smoothing and cleaning out depressions in the mould.

(*f*) *Swab*. A simple swab has a small brush having long hemp fibres. A bulb swab has a rubber bulb to hold the water and a soft hair brush at the open end. It is used for moistening the sand around the edge before the pattern is removed.

(*g*) *Bellow*. A hand operated bellow is used to blow loose particles of sand from the cavities and surface of the mould.

(*h*) *Trowel*. It consists of a metal blade with a wooden handle. The small trowels of various shapes are used for finishing and repairing mould cavaties as well as for smoothing over the parting surface of the mould.

(*i*) *Gate cutter*. It is a U-shaped piece of thin sheet. It is used for cutting a shallow trough in the mould to act as a passage for the hot metal.

(*j*) *Gaggers*. These are iron rods bent at one end or both ends. These are used for reinforcement of sand in the top of the moulding box and to support hanging bodies of sand.

2. *Moulding boxes* (*Flasks*). The sand moulds are prepared in a specially constructed boxes called flasks, which are open at the top and bottom. They are made in two parts, held in alignment by dowel pins. The top part is called the *cope* and the lower part as *drag*. If the flask is made in three pars, the intermediate part is called *a cheek*. These flasks can be made of either wood or metal.

3. *Moulding machines*. The various types of moulding machines are as follows:

(*a*) *Jolt machine*. It is used for ramming of sand in the mould. This machine rams the sand harder at the pattern face with decreasing hardness towards the back of the mould.

(*b*) *Squeezing machine*. This machine rams the sand harder at the back of the mould and softer on the pattern face. It is very usefull for shallow patterns.

(*c*) *Jolt-squeeze machine*. This machine produces uniform hardness of sand in the mould.

(*d*) *Sand slinger*. It is used for uniform packing of sand in the mould.

(*e*) *Diaphragm moulding machine*. It is used for uniform ramming and hardness of the sand in the flask.

(*f*) *Stripping plate machine*. It is used to draw the pattern from the mould.

14.11 Moulding and Core Making

The moulding is a process of making a cavity (or mould) out of sand by means of a pattern. The molten metal is poured into the moulds to produce castings. Sometimes, a casting is to be made hollow or with cavities in it. Such type of castings require the use of cores. A core is defined as a sand shape which is exactly similar to the cavities or holes to be provided in the castings. The cores are generally made separately *i.e.* they are not moulded with the pattern. The process of making cores is called *core making*.

The moulding materials commonly used in foundry practice are moulding sand, sand binders and sand additives. Quartz and other silica rocks are the source of silica sand which is commonly used for moulding. The binders added to the sand hold the sand grains together, imparts strength, resistance to erosion and breakage and degree of collapsibility. The binders may be clay-type, organic type and inorganic type binders. The sand additives (such as sea coal, wood flour and silica flour) are mixed with heap sand for improving some special features.

The moulding sand must posses the following properties:

1. *Porosity or permeability*. It is that property of sand which permits the steam and other gases to pass through the sand mould. The porosity of sand depends upon its grain size, grain shape, moisture and clay contents in the moulding sand. If the sand is too fine, its porosity will be low.

2. *Plasticity*. It is that property of sand due to which it flows to all portions of the moulding box or flask. The sand must have sufficient plasticity to produce a good mould.

3. *Adhesiveness*. It is that property of sand due to which it adhere or cling to the sides of the moulding box.

4. *Cohesiveness*. It is that property of sand due to which the sand grains stick together during ramming. It is defined as the strength of the moulding sand.

5. *Refractoriness.* It is that property of sand which enables it to resist high temperature of the molten metal without breaking down or fusing.

The moulding sands, according to their use, are classified as follows:

1. *Green sand.* The sand in its natural or moist state is called *green sand.* It is also called tempered sand. It is a mixture of silica sand with 20 to 30 percent clay, having total amount of water from 6 to 10 percent. The moulds prepared with this sand are called *green sand moulds.* The green sand moulds are used for small size castings of ferrous and non-ferrous metals.

2. *Dry sand.* The green sand moulds when baked or dried before pouring the molten metal are called *dry sand moulds.* The sand in this condition is called dry sand. The dry sand moulds have greater strength, rigidity and thermal stability. These moulds are used for large and heavy castings.

3. *Loam sand.* A mixture of 50 percent sand grains and 50 percent clay is called *loam sand.* It is used for loam moulding of large grey-iron castings.

4. *Facing sand.* A sand used for facing of the mould is called *facing sand.* It is a specially prepared sand from silica sand and clay, without the addition of used sand.

5. *Backing or floor sand.* A sand used to back up the facing sand and not used next to the pattern, is called *backing sand.* The sand which have been repeatedly used, may be employed for this purpose. It is sometimes called *black sand* because of its black colour.

6. *System sand.* A sand employed in mechanical sand preparation and handling system is called *system sand.* This sand has high strength, permeability and refractoriness.

7. *Parting sand.* A sand employed on the faces of the patterns before moulding is called *parting sand.* The parting sand consists of dried silica sand, sea sand or burnt sand.

8. *Core sand.* A sand used for the preparation of cores is called *core sand.* It is sometimes called *oil sand.* It is the silica sand mixed with linseed oil or any other oil as binder.

14.12 Gates and Risers

The passage-way which serves to deliver the molten metal into the mould cavity is known as *gating system.* A gating system consists of a pouring cup, a down gate or sprue, a runner and an ingate. There are various types of gates such as parting line gates, bottom gates, horn gate, branch gate and top gate.

A riser (or feed head) is an opening through the cope. Its main purpose is to feed the molten metal to the casting as it solidifies *i.e.*, to compensate for the shrinkage. The risers also serve as a large vent for generated steam and gases and afford a place for collecting loose sand or slag.

14.13 Cores

The cores are defined as sand bodies used to form the hollow portions or cavaties of desired shape and size in a casting. In addition to forming internal cavaties in the casting, the cores serve a number of purposes as follows:

1. The cores may be used to construct a complete mould.
2. The cores may be used to form a part of a green sand mould.
3. The cores strengthen or improve a mould surface.
4. The cores may be used as a part of the gating system.

The various types of cores, depending upon their position are horizontal cores, vertical cores, balanced cores, drop cores and cover cores or hanging cores.

14.14 Special Casting Processes

The sand moulds may be used for casting ferrous and non-ferrous metals, but these moulds can be used only once, because the mould is destroyed after the metal has solidified. This will increase the cost of production. The sand moulds also, can not maintain better tolerances and smooth surface finish. In order to meet these requirements, following casting methods may be used:

1. *Permanent mould casting.* A casting made by pouring molten metal by gravity into a mould made of some metallic alloy or other material of permanence is known as permanent mould casting. The term die casting is another name for this type of casting.

2. *Slush casting.* The slush casting is a special application involving the use of a permanent mould. It is used for casting low melting temperature alloys. This method is only adopted for ornaments and toys of non-ferrous alloys.

3. *Die casting.* The die casting (also known as pressure die casting) may be defined as that casting which uses the permanent mould (called die) and the molten metal is introduced into it by means of pressure. Following are the two types of die casting machines commonly used for die casting.

(*a*) *Hot chamber die casting machine.* In a hot chamber die casting machine, the melting pot is an integral part of the machine. The molten metal is forced in the die cavity at pressures from 7 to 14 MPa. The pressure may be obtained by the application of compressed air or by a hydraulically operated plunger. The hot chamber die casting machine is used for casting zinc, tin, lead and other low melting alloys.

(*b*) *Cold chamber die casting machine.* In a cold chamber die casting machine, the melting pot is usually separate from the machine and the molten metal is transferred to injection mechanism by ladle. The pressure on the casting metal in cold chamber die casting machine may vary from 21 to 210 MPa and in some cases may reach 700 MPa. This process is used for casting aluminium, magnesium, copper base alloys and other high melting alloys.

4. *Centrifugal casting.* A casting process in which molten metal is poured and allowed to solidify while the mould is revolving, is called centrifugal process. The castings produced under this centrifugal force is called centrifugal casting. This process is especially employed for casting articles of symmetrical shape. The ferrous and nonferrous metals can be casted by this process. The castings produced by this process have dense and fine grained structure.

5. *Investment casting.* It is also known as lost wax process or precision casting. The castings produced by this method are within very close tolerances ($\pm$ 0.05 mm) and do not require subsequent machining.

6. *Shell moulding process.* The shell moulding process is also called croning process. The shell cast parts can be produced with dimensional tolerances of $\pm$ 0.2 mm.

14.15 Defects in Casting

The defects in a casting may be due to pattern and moulding box equipment, moulding sand, cores, gating system or molten metal. Some of the defects are as follows:

1. *Mould shift.* It results in a mismatching of the top and bottom parts of a casting, usually at the parting line.

2. *Swell.* It is an enlargement of the mould cavity by molten metal pressure resulting in localised or general enlargement of the casting.

3. *Fins and flash.* These are thin projections of metal not intended as a part of casting. These usually occur at the parting line of the mould.

4. *Sand wash.* It usually occurs near the ingates as rough lumps on the surface of a casting.

5. *Shrinkage.* It is a crack in the casting or dishing on the surface of a casting which results from unequal contraction of the metal during solidification.

6. *Hot tear.* It is an internal or external ragged discontinuity in the metal casting resulting from hindered contraction occurring just after the metal has solidified.

7. *Sand blow or blow hole.* It is an excessively smooth depression on the outer surface of a casting.

8. *Honeycombing or slag holes.* These are smooth depressions on the upper surface of the casting. They usually occur near the ingates.

9. *Scabs.* These are patches of sand on the upper surface of the casting.

10. *Cold shuts and misruns.* These occur when the mould cavity is not completely filled and an incomplete casting results.

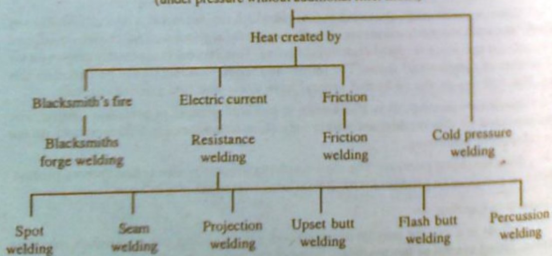
11. *Pour short.* It occurs when the mould cavity is not completely filled because of insufficient metal.

12. *Run-outs and bust-outs.* These permit drainage of the metal from the cavity and result in incomplete castings.

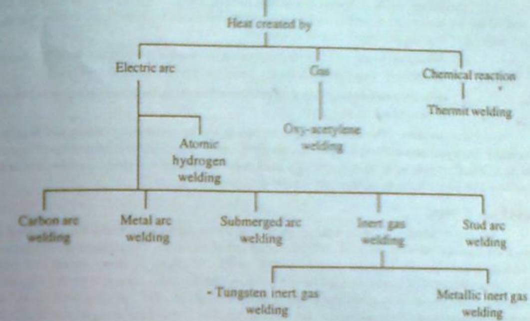
14.16 Welding

The welding is a process of joining two similar or dissimilar metals by fusion, with or without the application of pressure and with or without the use of filler metal. The welding is broadly divided into the following two groups:

1. Forge or pressure welding
(under pressure without additional filler metal)



2. Fusion or non-pressure welding
(With additional filler metal)



14.17 Types of Welded Joints

The commonly used joints in fusion welding are lap joint, butt joint, corner joint, edge joint and T-joint.

The lap joints are employed on plates having thickness less than 3 mm. In butt welds, the plate edges do not require bevelling if the thickness of plate is less than 5 mm. If the plate thickness is 5 mm to 12.5 mm, the edges should be bevelled to V or U-groove and plates having thickness above 12.5mm should have a V or U-groove on both sides.

14.18 Electric Resistance Welding

It is a type of pressure welding. It is used for joining pieces of sheet metal or wire. The welding heat is obtained at the location of the desired weld by the electrical resistance through the metal pieces to a relatively short duration, low voltage (from 6 to 10 volts only) high amperage (varying from 60 to 4000 amperes) electric current. The amount of current can be regulated by changing the primary turns of the transformer. When the area to be welded is sufficiently heated, the pressure varying from 25 to 55 MPa is applied to the joining area by suitable electrodes until the weld is solid. The various types of electric resistance welding are as follows:

1. *Spot welding.* It is used for welding lap joints, joining components made from plate material having 0.025 mm to 1.25 mm in thickness. The plates to be joined together are placed between the two electrode tips of copper or copper alloy. It may be noted that

(*a*) The electrode tip diameter (d) should be equal to $\sqrt{t}$, where t is the thickness of plate to be welded.

(*b*) The distance between the nearest edge of plate and centre of weld should be at least $1.5\,d$.

(*c*) The spacing between two spot welds should not be less than $3d$.

2. *Roll spot and seam welding.* When the spot welds on two over lapping pieces of metal are spaced, the process is known as roll spot welding. If the spot welds are sufficiently made close, then

the process is called seam welding. This process is best adopted for metal thickness ranging from 0.025 mm to 3 mm.

3. *Projection welding.* It is similar to spot welding except that one of the metal pieces to be welded has projections on its surface at the points where the welds are to be made. In other words, it is a multi-spot welding process. It may be noted that

(*a*) When two pieces of different metals are to be welded by projection welding, then the projections should be made on the metal piece with the higher conductivity.

(*b*) When the two metal pieces are of different thickness, the projections should be made on the thicker metal piece.

4. *Butt welding.* The butt welding is of two types, *i.e.* upset butt welding and flash butt welding. The upset butt welding is especially adopted to rods, pipes and many other parts of uniform section. The flash butt welding is extensively used in the manufacture of steel containers and in the welding of mild steel shanks to high speed drills and reamers.

14.19 Arc Welding

The arc welding is a fusion welding process is which the welding heat is obtained from an electric arc struck between the work (or base metal) and an electrode. The temperature of heat produced by the electric arc is of the order of 6000°C to 7000°C. Both the direct current (D.C.) and alternating current (A.C.) may be used for arc welding, but the direct current is prefered for most purposes. When the work is connected to the positive terminal of a D.C. welding machine and the negative terminal to an electrode holder, the welding set up is said to have *straight polarity*. On the other hand, when work is connected to negative and the electrode to a positive terminal, then the welding set up is said to have *reversed polarity*. The straight polarity is preferable for some welds while for other welds reversed polarity should be used.

Following are the two types of arc welding depending upon the type of electrode:

(*a*) *Un-shielded arc welding.* When a large electrode or filler rod is used for welding, it is said to be un-shielded arc welding.

(*b*) *Shielded arc welding.* When the welding rods coated with fluxing material are used, then it is called shielded arc welding.

14.20 Arc Welding Processes

The following are the various arc welding processes commonly used in engineering practice:

1. *Carbon arc welding.* In carbon arc welding, the welding heat is obtained from an electric arc between a carbon electrode and the work. In welding heavy plates, the additional metal is deposited in the weld from a filler rod.

2. *Metal arc welding.* In metal arc welding, the arc is produced between the metal electrode (also called filler rod) and the workpiece. During the welding process, the metal electrode is melted by the heat of the arc and fused with the work piece. The temperature produced by the heat is about 2400° C to 2700° C.

3. *Metallic inert-gas (M I G) arc welding.* In M I G welding, the electrode is consumable. The filler metal is deposited by the arc which is completely surrounded by an inert gas.

4. *Tungsten inert-gas (T I G) arc welding.* In T IG welding, the heat is produced from an arc between the non-consumable tungsten electrode and the workpiece. The welding zone is shielded by an atmosphere of inert gas (such as helium or argon) supplied from a suitable source. The direct current with straight polarity is used for welding copper alloys and stainless steel, whereas the reversed polarity is used for magnesium. The alternating current is more versatile in welding for steel, cast iron, aluminium and magnesium.

5. *Atomic hydrogen welding.* In atomic hydrogen welding, the arc is obtained between two tungsten electrodes (non-cosumable) while a stream of hydrogen passes by the arc and envelops the welding zone.

6. *Stud arc welding.* It is a direct current arc welding process and is used for welding metal studs to the flat metal surfaces.

7. *Submerged arc welding.* In submerged arc welding, the arc is produced between a bare metal electrode and the workpiece. The submerged arc welding is mostly done on low carbon and alloy steels, but it may be used on many of the non-ferrous metals.

8. *Thermit-welding.* In thermit welding, a mixture of iron oxide and aluminium known as thermit, is used. The mixture is ignited only at a temperature of about 1500° C. A major advantage of the thermit welding is that all parts of the weld section are molten at the same time and the weld cools almost uniformly. This results in a minimum problem with internal residual stresses.

The thermit welding is often used in joining iron and steel parts that are too large to be manufactured, such as rails, truck frames, locomotive frames, other large sections used on steam and rail roads, for stern frames, rudder frames etc. In steel mills, thermit electric welding is employed to replace broken gear teeth, to weld new necks on rolls and pinions and to repair broken shears.

14.21 Gas Welding

It is a type of fusion welding, in which the heat for welding is obtained by the combustion of a fuel gas. The most widely used gas combination for producing a hot flame for welding metals is oxygen and acetylene (C_2H_2). The approximate flame temperature produced by oxy-acetylene flame is 3200° C. The basic equipment required to carry out oxy- acetylene gas welding is as follows:

1. *Welding torch.* It is also known as blow pipe. It is a tool for mixing the oxygen and acetylene in the desired volumes and burning the mixture at the end of a tip, which produces a high temperature flame. The welding torches are commercially available in the following two types:

(*a*) Injector or low pressure type, and

(*b*) Positive or equal pressure (also known as high pressure) type.

The injector or low pressure type welding torch operates at an acetylene pressure of less than 7 kN / m^2. This low pressure acetylene is produced at the welding site by the chemical reaction between water and calcium carbide (CaC_2). The oxygen is, however, supplied at a pressure ranging from 70 to 280 kN/m^2 depending upon the tip size.

In positive or equal pressure type welding torch, the gases must by delivered to the torch at pressures generally above 7 kN / m^2.

2. *Welding torch tip.* The tips are made of high thermal conductivity material such as copper or copper alloy. The interchangeable tips for the various thicknesses are usually provided with each welding torch.

3. *Pressure regulators.* There are two gauges on the body of the regulator, one showing the pressure in the cylinder while the other shows pressure being supplied to the torch. The desired pressure at the welding torch for oxygen is between 70 and 280 kN / m^2 and for acetylene it is between 7 and 103 kN / m^2.

4. *Hose and hose fittings.* The standard colour for oxygen hose is black and for acetylene hose it is red.

5. *Gas cylinders.* The standard colour for oxygen cylinder is black and for acetylene cylinder it is maroon.

In addition to the above equipment, welding rods, fluxes, spark lighter, goggles and gloves are required for gas welding.

14.22 Gas Flame

The following three types of flames are used for gas welding.

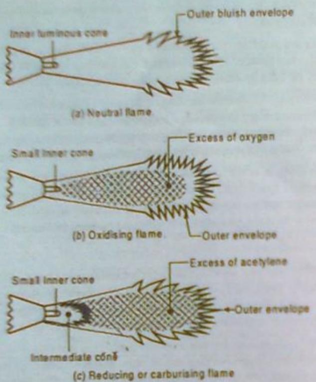


Fig. 14.2

1. *Neutral flame.* The neutral flame, as shown in Fig. 14.2 (*a*), is obtained by supplying equal volumes of oxygen and acetylene. It has the following two sharply defined zones:

(*i*) An inner luminous cone (3200° C), and

(*ii*) An outer cone or envelope of bluish colour (1250°C).

The most of the oxy-acetylene welding (*e.g.* welding of steel, cast iron, copper, aluminium etc.) is done with the neutral flame.

2. *Oxidising flame.* The oxidising flame, as shown in Fig. 14.2 (*b*), is obtained when there is an excess of oxygen. It is used for welding brass and bronze.

3. *Reducing or carburising flame.* The reducing flame, as shown in Fig. 14.2 (*c*), is obtained when there is an excess of acetylene. It is used for welding of molten metal, a certain alloy steels, many of non-ferrous, hard surfacing materials such as satellite.

14.23 Gas Welding Technique

The usual gas welding techniques in oxy-acetylene welding are as follows:

1. *Leftward or fore-hand welding.* In this method, the welding torch is held in the operator's right hand, the tip pointing towards the left and the weld is made from right to left. The torch makes an angle of 60°– 70° with the plate and the welding rod makes an angle of 30° – 40°. The plates above 6 mm thickness are not economical to weld with this method.

2. *Right-ward or back-hand welding.* In this method, the welding torch is held in the right hand and the filler rod in the left-hand. The welding begins at the left hand end of the joint and

proceeds towards the right. The torch makes an angle of 40° – 50° with the plate and the welding rod makes an angle of 30° – 40°. This method is better and economical for plates over 6 mm thickness.

3. *Vertical welding.* The vertical welding may be carried out either by the left-ward technique or by the right-ward technique. The great advantage of vertical welding is that the plate edge preparation is not required upto 16 mm thickness.

4. *Linde welding.* It is a special welding technique in which the use of oxy-acetylene flame with excess acetylene is made and the right-ward technique is used.

14.24 Gas or Oxygen Cutting of Metals

The cutting of iron and steel by using oxygen is extensively used now-a-days in industry. It is performed by an ordinary gas welding equipment, except that the welding torch is replaced by a cutting torch which consists of four openings.

14.25 Sheet Metal Work

It deals with the working of metal sheets. The various operations performed in a sheet metal shop are as follows:

1. *Marking.* It consists of scratching of lines on the surface of a sheet metal. It is also called scribing operation.

2. *Slitting.* The operation of cutting a sheet of metal in a straight line along the length is called slitting.

3. *Notching.* The removal of metal to the desired shape from the edge of a plate is called notching.

4. *Punching.* The operation of cutting a cylindrical hole in a sheet of metal by the punch and the die is called punching.

5. *Piercing.* The operation of cutting a hole (other than cylindrical) in the sheet of metal by the punch and the die is called piercing.

6. *Perforating.* The operation of cutting a number of holes evenly spaced in a regular pattern on a sheet of metal is called perforating.

7. *Blanking.* The operation of cutting of flat sheet to the desired shape is called blanking.

8. *Forming.* The operation of bending a sheet of metal along a curved axis is known as forming.

9. *Lancing.* The operation of cutting a sheet of metal through part of its length and then bending the cut portion is called lancing.

10. *Drawing.* The operation of producing cupshaped parts from flat sheet metal blanks by bending and plastic flow of metal is called drawing.

11. *Embossing.* The operation of giving impressions of figures, letters or designs on sheet metal parts is known as embossing.

12. *Planishing.* The operation of straightening a curved sheet metal is known as planishing.

14.26 Die and Punch

A die is a female part of a complete tool for producing work in a press. A punch is a male component of the die assembly, which is directly or indirectly moved by the press ram. The dies may be classified as follows:

1. *According to the type of press operation.* According to this criterion, the dies may be classified as cutting dies and forming dies. The cutting dies are used to cut the metal. The common cutting dies are blanking dies, piercing dies, perforating dies etc.

The forming dies change the appearance of the blank without removing any stock. These dies include bending dies, drawing dies, etc.

2. *According to the method of operation.* According to this criterion, the dies may be classified as simple dies, compound dies, combination dies and progressive dies.

In a *simple die*, only one operation is performed for each stroke of the press ram.

In a *compound die*, two or more cutting operations are performed at one station of the press in every stroke of the ram. The washer is produced by simultaneous blanking and piercing operations in a compound die.

In a *combination die*, two or more operations are performed simultaneously at one station in the single stroke of the ram. It differs from compound die in that the cutting operation is combined with a bending or forming operation in a combination die.

In a *progressive die*, two or more operations are performed simultaneously, but at different stations.

14.27 Bench Work and Fitting

The bench work and fitting plays an important role in every engineering workshop to complete and finish the job to the desired accuracy. The work carried out by hand at the bench is called bench work, whereas fitting is the assembling of parts together by filing, chipping, sawing, scraping, tapping etc., necessary after the machine operation. The various tools used in fitting practice are as follows:

1. *Holding tools.* The holding tools or vices are required to hold the work firmly. The various types of vices for different purposes are bench vice, hand vice, pipe vice, leg vice and pin vice.

2. *Striking tools.* The striking tools or hammers are used to strike the job or tool. The various types of hammers in common use are ball-peen hammer, cross-peen hammer, straight-peen hammer, double-faced hammer, and soft hammer.

3. *Cutting tools.* The chief cutting tools used in fitting are cold chisels, hacksaws and files. These tools are discussed, in brief, as follows:

(*a*) *Cold chisels.* These are used to cut the cold metal and are made by forging from cast tool steel of octagonal cross-section. The cutting edge is ground to an angle suited to the material being worked upon. After forging to shape and roughly grinding, the cutting edge should be hardened and tempered. The most commonly used cutting angle is 60°, but this varies according to the type of material cut. The various types of chisels commonly used for fitting are flat chisel, cross-cut chisel or cape chisel, half-round chisel, diamond pointed chisel and side chisel.

(*b*) *Hacksaws.* The hacksaw is the chief tool used by the fitter for cutting rods, bars, and pipes into desired lengths. The cutting blades of hacksaw are made of carbon or high speed steel. The blades are specified by its length and the point or pitch. The length of the blade is the distance between the outside edges of the holes which fit over the pins. The point or pitch is measured by the number of teeth per 25 mm length. The points of the teeth are bent to cut a wide groove and prevents the body of the blade from rubbing or jamming in the saw cut. This bending of the teeth to the sides is called the *setting* of the teeth. Usually alternate teeth are set to right and left, every third or fifth tooth left straight to break up the chips and help the teeth to clear themselves.

(*c*) *Files.* A file is a hardened piece of high grade steel with slanting rows of teeth. It is used to cut, smooth or fit metal parts. The size of the file is indicated by it length. It may be noted that coarseness or pitch of the file varies directly as the length of the file. Thus larger the length of the file, coarser will be the pitch and smaller the file, finer will be the pitch.

4. *Marking, Measuring and testing tools.* The various marking, measuring and testing tools are Engineer's steel rule, outside and inside calipers, divider, surface plate, scriber, universal surface gauge, punch, V-block, angle plate, try square, combination set etc.

14.28 Measuring Instruments and Gauges

The measuring instruments are dimensional control instruments used to measure the exact size of object. These are adjustable devices and can measure with an accuracy of 0.001 mm or better.

The gauges are fixed dimension instruments and are not graduated. In most cases, these have no adjustable member for measuring varying dimensions of lengths and angles.

Some important measuring instruments and gauges are discussed, in brief, as follows:

1. *Outside micrometer.* It is mainly used to measure the outside diameter of a job or length of a small part, to an accuracy of 0.01 mm.

2. *Inside micrometer.* It is used to measure large internal diameters (over 50 mm) to an accuracy of 0.01 mm.

3. *Screw thread micrometer.* It is used to measure the pitch diameter of screw threads to an accuracy of 0.01 mm.

4. *Depth gauge micrometer.* It is used to measure the depth of holes, slots and recessed areas to an accuracy of 0.01 mm.

5. *Vernier caliper.* It is used to measure external as well as internal diameters of shafts, thickness of parts, depth of slots and holes, to an accuracy of 0.02 mm.

6. *Vernier height gauge.* It is mainly used to measure heights of parts to an accuracy of 0.02 mm.

7. *Vernier depth gauge.* It is used to measure the depth of holes, recesses, and distances from plane surface to a projection, to an accuracy of 0.02 mm.

8. *Combination set.* It is an extremely useful instrument and has all the essential features of try square, bevel protractor, rule and scriber.

9. *Universal bevel protractor.* It is also called vernier bevel protractor. It is used for measuring and testing angles, within the limits of 5 minutes (1/12 of a degree).

10. *Sine bar.* It is used either to measure angles more precisely than a bevel protractor or for locating any work to a given angle within very close limits. It is generally used with slip gauges.

11. *Ring gauge.* It is used to check the diameter of shafts or studs.

12. *Plug gauge.* It is used to test the accuracy of holes. The standard plug gauge is used in general engineering workshop, tool rooms etc. The limit plug gauge is used where large quantities are to be produced. The single-ended limit plug gauge has separate 'Go' and 'Not go' members. The progressive limit plug gauge has 'Go' and Not go' members on the same side of a handle.

13. *Snap gauge.* It is used to check the external dimension.

14. *Slip gauge.* It is used to check the accuracy of micrometers, calipers, snap gauges, dial indicators etc.

15. *Feeler gauge.* It is used to check the clearances between two mating surfaces.

OBJECTIVE TYPE QUESTIONS

1. The metal is subjected to mechanical working for

(*a*) refining grain size	(*b*) reducing original block into desired shape
(*c*) controlling the direction of flow lines	(*d*) all of these

2. The temperature at which the new grains are formed in the metal is called

(*a*) lower critical temperature	(*b*) upper critical temperature
(*c*) eutectic temperature	(*d*) recrystallisation temperature

15

Production Engineering

15.1 Introduction

The subject Production Engineering deals with the metal cutting or machining, cutting tools, measurement of cutting forces, grinding, boring, gear manufacturing, jigs and fixtures etc.

15.2 Mechanics of Metal Cutting

There are two methods of metal cutting, *i.e.* orthogonal cutting or two dimensional cutting and oblique cutting or three dimensional cutting. In ***orthogonal cutting*** of metals, the cutting edge of the tool is perpendicular to the direction of the tool travel. In ***oblique cutting*** of metals, the cutting edge of the tool is inclined at an angle less than 90° to the direction of tool travel. The following three types of chips are produced during metal cutting or machining:

1. *Discontinuous chips.* These types of chips are usually formed during machining of brittle materials like cast iron. The low cutting speed and small rake angle of the tool are responsible for the formation of discontinuous chips.

2. *Continuous chips.* These types of chips are produced during machining of ductile materials like mild steel. The high cutting speed and large rake angle of the tool will result in the formation of continuous chips. These chips are in the form of long coils having the same thickness throughout.

3. ***Continuous chips with built up edge.*** These types of chips are also produced during machining of ductile materials. The low cutting speed and small rake angle of the tool will result in the formation of continuous chips with built up edge. These chips are also formed when the cutting edge of the tool is dull.

15.3 Methods of Machining

Following are the two methods of metal cutting depending upon the arrangement of cutting edge with respect to the direction of tool travel:

1. ***Orthogonal cutting or two dimensional cutting.*** In orthogonal cutting, the cutting edge of the tool is perpendicular to the direction of tool travel. The cutting edge clears the width of the workpiece on either ends. The chip flows over the tool face and the direction of the chip flow velocity is normal to the cutting edge. The maximum chip thickness occurs at the middle.

2. ***Oblique cutting or three dimensional cutting.*** In oblique cutting, the cutting edge of the tool is inclined at an angle less than 90° to the direction of tool travel. Frequently, more than one cutting edges are in action. The cutting edge may not clear the width of the work piece. The chip flows on the tool face at an angle less than 90° with the normal on the cutting edge. The maximum chip thickness may not occur at the middle.

15.4 Metal Cutting Tool (Single Point Cutting Tool)

A single point cutting tool is mostly used on lathe, shaper and planer while a multi-point cutting tool is used on milling machine and broaching machine. A single point cutting tool may be either left or right hand cut tool depending upon the direction of feed. A right hand tool is shown in Fig. 15.1. The following definition may be clearly understood:

(*a*) ***Shank.*** It is the main body of the tool.

(*b*) ***Face.*** It is the surface on which the chip slides.

(*c*) ***Flank.*** It is the surface below and adjacent to the cutting edge.

(*d*) ***Heel.*** It is the intersection of the flank and base of the tool.

(*e*) ***Nose.*** It is the intersection of side cutting edge and end cutting edge.

(*f*) ***Cutting edge.*** It is the edge on the face of the tool which removes the material from the work piece.

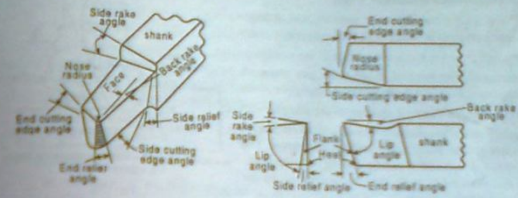


Fig. 15.1

(*g*) ***Lip angle.*** It is the angle between the tool face and ground end surface of flank. The lip angle of a single point tool is usually 60° to 80°.

(*h*) ***Cutting angle.*** It is the angle between the face of the tool and a line tangent to the machined surface at the cutting point.

(*i*) ***Rake angle.*** The angle made by the face of the tool and the plane parallel to the base of the cutting tool. The strength of the tool depends upon this angle. The rake angle required to machine brass by high speed tool is 0°.

The angle by which the face of the tool is inclined towards back, is called *back rake angle*.

The angle by which the face of the tool is inclined towards side, is called *side rake angle*. It is provided on tools to control chip flow.

The negative rake is usually provided on cemented carbide tools.

(*j*) ***Side relief angle.*** It is the angle between the surface of the flank immediately below the point and a plane at right angles to the centre line of the point of tool.

(*k*) ***End relief angle.*** It is the angle between the surface of the flank immediately below the point and a line drawn from the point perpendicular to the base.

15.5 Tool Wear

The tool wear or tool failure may be due to the following:

(*a*) cracking at the cutting edge due to thermal stresses,

(*b*) chipping of the cutting edge,

(*c*) plastic deformation of the cutting edge, and

(*d*) flank and crater wear.

The ***flank wear*** is due to the abrasive action of hard mis-constituents including debris from built up edge as the work material rubs the work surface. It depends upon the amount and distribution of hard constituents in the work material. The flank wear occurs mainly on the nose part, front relief face and side relief face of the cutting tool.

The *crater wear* is usually found while machining brittle materials. It occurs mainly due to diffusion of metals. It leads to increase in cutting temperature, weakening of tool, friction and cutting forces. The crater wear occurs mainly on the face of the cutting tool at a short distance from the cutting edge only.

15.6 Determination of Shear Angle

Fig. 15.2 shows the basic mechanics of orthogonal cutting process in which a tool of rake angle α and relief angle β moves along the surface of the workpiece at a depth of t. The material ahead of the tool gets work hardened and is sheared continuously along the shear plane inclined at an angle ϕ (known as shear angle) with the surface of the workpiece. The chip thickness (t_c) is dependent on the shear angle and the rake angle. The ratio of t / t_c is called the cutting ratio (r) or chip-thickness ratio. The shear angle may be determined by the following relation :

α = Rake angle, β = Relief or clearance angle, ϕ = Shear angle

Fig. 15.2

$$\tan \phi = \frac{r \cos \alpha}{1 - r \sin \alpha}$$

Notes: (*a*) The velocity of the tool relative to the workpiece is known as *cutting velocity*.

(*b*) The velocity of the tool along the tool face is known as *chip velocity*.

(*c*) The parameter which completely defines the chip formation in a metal cutting process is shear angle and chip-tool contact length.

(*d*) When the shear angle is small, the path of shear is large and the chip is thick. On the other hand, when the shear angle is large, the path of shear is short and the chip is thin.

15.7 Tool Life

The tool life may be defined as tool's useful life which has been expended when it can no longer produce satisfactory parts. The tool life is said to be over if poor surface finish is obtained and there is sudden increase in cutting forces and power consumption. The tool life is also said to be over if overheating and fuming due to heat of friction starts. The various factors which affects the tool life are tool geometry, cutting speed, feed, feed rate, depth of cut, microstructure, and chip thickness. The relation between the tool life (T) in minutes and cutting speed (V) in m / min is given by

$$V T^n = C$$

where C = A constant, and

n = An exponent, which depends upon the tool and work piece

= 0.1 to 0.2 for high speed steel tools

= 0.20 to 0.25 for carbide tools

= 0.4 to 0.55 for ceramic tools

It may be noted that

(*a*) The tool life decreases as the cutting speed increases.

(*b*) The larger end cutting edge angle of the tool increases tool life.

(*c*) The side cutting edge angle (larger then 15°) produces chipping and decreases tool life.

(*d*) The small nose radius results in excessive stress concentration and greater heat generation.

(*e*) The tool life, in case of continuous cutting, is much better than intermittent cutting.

(*f*) The tool life is better, if the grain size is larger.

(*g*) When the shear angle is large and the chip-tool contact area is low, then the tool life will be more.

15.8 Surface Roughness

In machining metals, surface roughness is due to the following factors:

1. Cutting tool vibrations; 2. Roughness of the cutting edge; 3. Feed marks or ridges left by the cutting tool; 4. Fragment of built-up edge on the machined surface; 5. Formation of discontinuous chips when cutting brittle materials, 6. Tearing of the ductile work material when machining at low cutting speeds; and 7. Defects in the structure of the work material.

The surface finish is improved by the increase in cutting speed, nose radius and true rake angle of the tool. The increase in depth of cut and feed rate will deteriorate the surface finish.

15.9 Tool Material

The tool material, for faster machining, should have wear resistance, red hardness and toughness. The principal materials used in cutting tools are as follows:

1. *High carbon steel.* The tools made of high carbon steel have low heat and wear resistance. Since these tools lose hardness at about 300° C, therefore they are not suitable for high cutting speeds and heavy-duty work. Such tools may be used on soft materials such as wood.

2. *High speed steel.* The high speed steel containing 18% tungsten, 4% chromium and 1% vanadium is considered to be one of the best all-purpose tool steel. They retain their hardness upto a temperature of 900° C.

3. *Carbide.* A carbide suitable for steel machining consists of 82% tungsten carbide, 10% titanium carbide and 8% cobalt. The carbide tools operating at very low cutting speeds (below 30 m/min) reduces tool life.

4. *Ceramic.* The ceramic tools are fixed to a tool body by brazing. These tools have greater tool life than carbide tools.

15.10 Lathe

The engine or centre lathe is a general purpose lathe and is widely used in workshops. The cutting tool may be fed both in *cross and longitudinal direction with reference to the lathe axis. The size of a lathe is specified by

1. The height of the centres above the top of the bed.
2. The swing or the maximum diameter of the work that can be rotated over the ways of the bed.
3. The maximum length of the work that can be accomodated between the lathe centres.
4. The maximum diameter of the work that can be rotated over the lathe spindle.

The principal parts of a lathe are bed, head stock, tail stock, **carriage and feed mechanism.

* The feed is said to be longitudinal when the tool moves parallel to the work. The feed is cross, when the tool moves perpendicular to the work.

** The carriage has five major parts, *i.e.* saddle, cross-slide, compound rest, tool post and apron.

The various lathe accessories used for holding and supporting the work are as follows:

(*a*) *Centres.* There are two types of lathe centres *i.e.* live centre and dead centre. These centres have standard Morse taper shank at one end and a 60° point at the other end.

(*b*) *Chucks.* A chuck is used for holding and rotating the workpiece in a lathe. The various types of chucks are three jaw universal chuck, four jaw independent chuck, combination chuck, magnetic chuck, collect chuck and air or hydraulic chuck.

(*c*) *Mandrels.* A lathe mandrel is a cylindrical bar with centre hole at each end. It is used to hold hollow workpieces to machine their external surface.

(*d*) *Lathe dog or carrier.* The work placed on a mandrel or held between centres is rotated positively by clamping the dog or carrier to the end of the work.

15.11 Lathe Operations

The most common operations which can be carried out on a lathe are as follows:

1. *Plain turning.* It is an operation of removing excess amount of material from the surface of the cylindrical workpiece.

2. *Step turning.* It is an operation of producing various steps of different diameters in the workpiece.

3. *Taper turning.* It is an operation of producing an external conical surface on a work piece. A small taper may be produced with the help of a forming tool or chamfering tool, but the larger tapers are produced by swivelling the compound rest at the required angle or by offsetting the tail stock or by taper turning attachment.

4. *Undercutting or Grooving.* It is an operation of reducing the diameter of a workpiece over a very narrow surface.

5. *Threading.* It is an operation of cutting helical grooves on the external cylindrical surface of workpiece.

6. *Knurling.* It is an operation of providing knurled (diamond shaped pattern) surface on the workpiece.

7. *Chamfering.* It is an operation of bevelling the extreme end of a workpiece. It is an essential operation after thread cutting.

8. *Boring.* It is an operation of enlarging of a hole already made in a workpiece.

15.12 Drilling

The operation of making round holes in metal pieces is known as drilling. In drilling operation, the metal is removed by shearing and extrusion. The drilling is done with the help of a drilling machine. Following are the various types of drilling machines:

(*a*) Portable drilling machine; (*b*) Sensitive drilling machine; (*c*) Radial drilling machine;

(*d*) Gang drilling machine; (*e*) Multiple spindle drilling machine; and

(*f*) Deep hole drilling machine.

The most common operations which can be carried on a drilling machine are as follows:

(*a*) *Boring.* It is an operation of enlarging a hole that has already been drilled.

(*b*) *Reaming.* It is an operation of slightly enlarging a machined hole to proper size with a smooth finish.

(*c*) *Tapping.* It is an operation of producing internal threads in a hole by means of a tool called tap. The hole drilled for tapping should be smaller than the tape size by twice the depth of thread.

(*d*) *Counter boring.* It is an operation of enlarging the mouth of a drilled hole to set bolt heads. The cutting speed for counter boring should be greater than that of drilling operation.

(*e*) *Spot facing.* It is an operation of smoothing and squaring the surface around a hole.

(*f*) *Counter-sinkning.* It is an operation of making a cone-shaped enlargement of the end of a hole.

(*g*) *Lapping.* It is an operation of sizing and finishing a small diameter hole.

(*h*) *Tre-panning.* It is an operation of producing a hole by removing metal along the circumference of a hollow cutting tool.

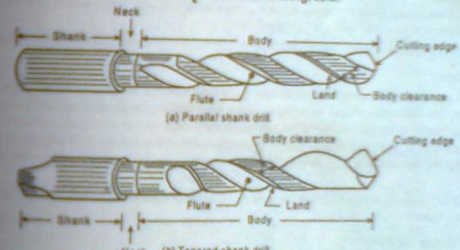
15.13 Drilling Tools

The drilling tools called drills are used for making round holes in the work. The following types of drills are commonly used:

1. *Flat drill.* It is a simple type of drill and has two cutting edges bevelled at 60°.

2. *Straight fluted drill.* It is used for making holes in brass, copper and other soft metals. It is considered as a cutting tool having zero rake.

3. *Twist drill.* It is an end cutting tool with two, three or four cutting lips. It has a cylindrical body on which the grooves are cuts. These grooves are called flutes. While drilling, the drill is held by a shank. The shank may be parallel or tapered as shown in Fig. 15.3.



(*a*) Parallel shank drill.

(*b*) Tapered shank drill.

Fig. 15.3

The parallel shank is provided on small sized drills (*i.e.* upto 12.5 mm). The tapered shank drills have a taper called Morse taper. The twist drills are made of either cabon steel or high speed steel. It is specified by its shank, material and diameter. The various angles of the twist drill are as follows:

1. *Point angle.* It is the angle included between the two lips projected upon a plane parallel to the drill axis and parallel to the two cutting lips. Its usual value is 118° and varies from metal to metal. The point angle is 90° for bakellite and fibrous plastic ; 118° for mild steel and brass and 135° for stainless steel. In general, the point angle is kept less than 118° for softer materials and more than 118° for harder alloy steel.

2. *Lip relief (clearance) angle.* It is the angle formed by the flank and a plane at right angles to the drill axis. This angle varies from 12° to 15°. This angle may be increased for drilling soft materials under heavy feeds.

3. *Chisel edge angle.* It is the obtuse angle included between the chisel edge and the lip as

viewed from the end of the drill. This angle is usually 120° to 135°.

4. *Helix or rake angle.* It is the angle formed by the leading edge of the land with a plane having the axis of the drill. Its usual value is 30°. A drill with low helix angle is used in drilling brass whereas a drill with high helix angle is used in drilling aluminium.

15.14 Cutting Speed for Drilling

The cutting speed of a drill depends upon the material of the drill, type of the material to be drilled, type of coolant used and the quality of surface finish desired. It varies from point to point on the cutting edge of the drill. The maximum speed occurs at the periphery of the drill. It may be noted that for drilling softer materials, the cutting speed is high as compared to harder materials.

The average cutting speed for different materials using high speed steel twist drill are as follows:

Table 15.1. Cutting speed in m/min.

Material	Mild steel	Copper	Aluminium, brass and bronze	Stainless steel
Cutting speed (m/min)	24 – 45	18 – 30	60 – 90	12 – 18

Notes: 1. The cutting speed for drilling aluminium, brass and bronze with carbon steel drills is equal to the cutting speed for drilling mild steel with high speed steel drills.

2. The high speed steel drills can be operated at about double the speed of high carbon steel drills.

15.15 Taps

A tap is used for cutting internal threads into a hole. The taps are usually made in sets of three to cut any particular size. These are called taper tap, intermediate (or second) tap and bottoming (or plug) tap. The taper tap has its leading end tapered off for a length of 8 to 10 threads and this is the first tap to use. The second tap has only two or three threads chamfered and follows the taper tap. The threads on the bottoming or plug tap runs to its extreme end. This tap is used to cut threads in a blind hole.

Note: For tapping, the hole to be drilled is smaller than the outside diameter of the thread on the tap *i.e.* equal to the core diameter.

15.16 Shaper and Planer

A shaper is a reciprocating type of machine tool used for producing small flat surfaces with the help of a single point tool reciprocating over the stationary workpiece. The flat surface may be horizontal, inclined or vertical. In a shaper, the tool is held in the tool post of the reciprocating ram and performs the cutting operation during its forward stroke.

A planer is a machine tool used to produce plane and flat surface by a single point cutting tool. The fundamental difference between a shaper and planer is that in a planer, the tool remains stationary and the work reciprocates whereas in a shaper, the work remains stationary and the tool reciprocates.

15.17 Grinding

The grinding is the process of removing metal by the use of grinding wheels. The grinding wheel is made of abrasive grains which form the cutting edges in a wheel. The size of the abrasive grain required in a grinding wheel depends upon the hardness of the material being ground. There are two types of abrasives *i.e.* natural abrasives and artificial abrasives. The natural abrasives are corun-

dum and emery and the artificial abrasives are *silicon carbide (the trade name is carborundum) and **aluminium oxide (the trade name is aloxite). The grinding wheels made from coarse grained abrasives are used for fast removal of materials whereas fine grained wheels are used for finish of work. The coarse grained wheels may be used for grinding soft materials and fine grained wheels for hard and brittle materials.

The hardness of a grinding wheel is specified by a letter of alphabet. The alphabets A to H are soft grades, I to P are medium grades and Q to Z are hard grades. The soft grade grinding wheels are used for grinding hard materials and hard grade grinding wheels for softer materials. A soft grade grinding wheel is one in which the abrasive grains can be easily dislodged and in a hard grade grinding wheel, the abrasive grains are held more securely.

The structure of a grinding wheel depends upon the nature of the grinding operation, hardness of the material being ground and the finish required. A higher proportion of bond in a grinding wheel renders an *open* or *coarse structure* and a lower proportion of it leads to a *close* or *dense structure*. An open or coarse structure of a grinding wheel is suitable for heavy cuts, soft, tough and ductile materials. The close or dense structure of a grinding wheel is suitable for finishing cuts, hard and brittle materials.

An open structure of a grinding wheel is denoted by 9 to 15 or higher whereas dense structure is denoted by 1 to 8.

When the cutting edge of a grinding wheel takes a glass-like appearance due to wear of abrasive grains, then it is called *glazing* of the grinding wheel. It decreases the rate of grinding. The glazing in grinding wheels takes place when the wheel is too hard or it revolves at a very high speed. Thus the glazing may be decreased by using a softer wheel or decreasing the wheel speed.

The process of changing the shape of grinding wheel as it becomes worn due to breaking away of the abrasive and bond is called *truing*.

The process of improving the cutting action of the grinding wheel is called *dressing*.

15.18 Grinding Operations

The following grinding operations are commonly used for grinding various types of work:

1. *Cylindrical grinding.* The cylindrical grinding may be internal or external. The method of grinding used to produce internal cylindrical holes and tapers is called internal cylindrical grinding. The method of grinding used to produce a straight or tapered surface on a workpiece is called external cylindrical grinding.

2. *Surface grinding.* The surface grinding is used to produce flat surface in a horizontal position.

3. *Face grinding.* The face grinding is used to produce flat surface in a vertical position.

4. *Form grinding.* The form grinding is used to grind gear teeth, threads, splined shafts and holes.

5. *Plunge grinding.* The plunge grinding is used to grind external diameter of a work piece equal to or shorter in length than the width of the wheel face by feeding the revolving wheel into the work.

6. *Snag grinding.* The snag grinding is done to remove considerable amount of metal without regard to accuracy of the finished surface, *e.g.* trimming the surfaces left by sprues and risers on castings, removing the excess metal on a weld or grinding the parting line left on a casting or a forging.

7. *Centreless grinding.* The centreless grinding is the process of grinding the diameter of a

---

* The silicon carbide is recommended for grinding materials of low tensile strength. It is chiefly used for grinding cast iron, brass, bronze, ceramic and cemented carbide.

** The aluminium oxide is recommended for grinding materials of high tensile strength. It is chiefly used for grinding wrought iron, carbon steel, annealed malleable iron and high speed steel.

work piece not mounted on centres or otherwise held. The centreless grinding may be external or internal. In external centreless grinding, as shown in Fig. 15.4, the workpiece is placed on the work rest blade between the grinding wheel and regulating wheel. The grinding and regulating wheels rotate in the same direction but at different speeds. The surface speed of the regulating wheel is about 15 to 60 m / min and the grinding wheel rotates at a surface speed of 1500 to 2000 m / min. The axial movement of the work past the grinding wheel is obtained by tilting the wheel at a slight angle from the horizontal. An angular adjustment of 0 to 10° is provided to the regulating wheel. The actual feed (F) in centreless grinders is given by

$$F = \pi\, d\, n \sin \alpha$$

where N = Revolutions per minute,

d = Diameter of the regulating wheel,

α = Angle of inclination of the regulating wheel.

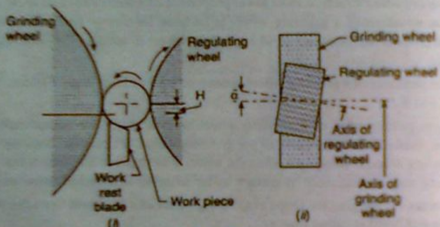


Fig. 15.4

There are three methods of feeding the workpiece. These methods are through feed grinding, infeed grinding and end feed grinding. The *through feed grinding* is extensively used for grinding long, slender shafts or bars. The *infeed grinding* is used to grind shoulders and formed surfaces. The *end feed grinding* is used to produce tapers.

15.19 Milling Machine

A milling machine is used to produce flat or profiled surfaces, grooves or slots with the help of a revolving multiple tooth cutter. The different types of milling machines are as follows:

(*a*) Column and knee type milling machine; (*b*) Vertical milling machine;

(*c*) Plain milling machine; (*d*) Hand milling machine; (*e*) Universal milling machine;

(*f*) Omniversal milling machine; (*g*) Plano milling machine; (*h*) Profiling machine;

(*i*) Planetary milling machine; and (*j*) Pantograph milling machine.

15.20 Up Milling and Down Milling

The process of removing metal by a cutter which is rotated against the direction of travel of the workpiece is called *up-milling*. It is also called conventional milling. In up-milling, the chip thickness is minimum at the beginning of the cut and maximum at the end of cut. The cutting force varies from zero to maximum.

The process of removing metal by a cutter which is rotated in the same direction of travel of the workpiece is called *down milling*. It is also called climb milling. In down milling, the chip thickness is maximum at the beginning of the cut and minimum at the end of cut. The cutting force varies from maximum to zero.

15.21 Milling Operations

The main milling operations are as follows:

1. *Plain or slab milling*. It is an operation of producing flat or horizontal surface parallel to the axis of the cutter.

2. *Face milling*. It is an operation of producing flat surface at right angles to the axis of the rotation of cutter.

3. *Angular or bevel milling*. It is an operation of producing flat surface at an angle to the axis of the cutter.

4. *Side milling*. It is an operation of producing vertical flat surface on the side face of a job by using a side milling cutter.

5. *End milling*. It is an operation of producing flat surfaces either horizontal, vertical or at an angle by using an end milling cutter.

6. *Form milling*. It is an operation of producing surfaces of irregular shape. The cutter (known as form or profile cutter) has the same profile corresponding to the surface to be produced.

7. *Gang milling*. It is an operation of producing many surfaces of a workpiece simultaneously by feeding the table against a number of required cutters.

8. *Saw milling*. It is an operation of producing narrow slots or grooves on a workpiece.

9. *Helical or spiral milling*. It is an operation of producing grooves around the periphery of a cylindrical or conical workpiece.

15.22 Indexing

The method of dividing the periphery of a job into equal number of divisions is called *indexing*. There are mainly four indexing methods, *i.e.* direct indexing, simple or plain indexing, compound indexing and differential indexing.

15.23 Jigs and Fixtures

A Jig is defined as a device which holds and locates a work piece and guides and controls one or more cutting tools. The jigs are used for holding and guiding the tool in drilling, reaming or tapping operations.

A fixture is defined as a device which holds and locates a workpiece during an inspection or for a manufacturing operation. The fixtures are used for holding the work in milling, grinding, planing or turning operations.

15.24 Broaching

The broaching is a process of removing metal by pushing or pulling a cutting tool (known as broach) having a number of teeth gradually increasing in size. The broach has three cutting zones, *i.e.* roughing teeth, semi-finishing teeth and finishing teeth. The teeth are gradually increasing in height from the first roughing tooth to the first of the finishing tooth, according to the required profile of the workpiece. The rear teeth of a broach removes maximum metal. The broaching is applied for machining a key way in a hole, internal and external surfaces, round and irregular shaped holes, external flat and contoured surfaces, and teeth of a gear or spline. The advantages of a broaching operation are as follows:

1. High accuracy and high class of surface finish is possible.
2. Rate of production is very high.
3. A little skill is required.
4. Roughing and finishing cuts are completed in one pass of the tool.

The various broaching operations are as follows:

(a) *Surface broaching*. The broaching operation in which either the work or the tool moves across the other, is known as surface broaching.

(b) *Continuous broaching*. The broaching operation in which the work moves past the stationary tool, is called continuous broaching.

(c) *Pull broaching*. The broaching operation in which the tool is pulled through the stationary work, is called pull broaching.

(d) *Push broaching*. The broaching operation in which the tool is pushed through the stationary work, is called push broaching. The push broach as compared to pull broach has less number of cutting teeth and removes less material for each pass of the tool.

15.25 Modern Machining Processes

The modern machining processes use four fundamental types of machining energy (*i.e.* mechanical, electrical, electrochemical and thermoelectric) directly to the workpiece. The material is removed with almost no physical contact of the tool and workpiece.

Following are some modern machining processes:

1. *Ultra sonic machining*. In ultra sonic machining, the metal is removed by using abrasive slurry between the tool and work. The abrasive slurry contains fine particles of aluminium oxide or silicon carbide or boron carbide and water. The vibratory tool (made of brass or copper) striking on the flow of abrasive slurry, causes thousands of microscopic abrasive grains to remove the work material by abrasion. The ultra sonic machining is best suited for tool steels, sintered carbides, glass, plastics etc. This type of machining may be used for machining of hard and brittle materials. It cuts materials at very slow speeds and produces good surface finish.

2. *Electrochemical machining*. In electrochemical machining (E C M), the metal is removed by maintaining an electrolyte between the tool and work in a very small gap (about 0.75 mm) between the two. The solution of sodium chloride in water is mostly used as electrolyte.

3. *Electro discharge machining*. In electro discharge machining, (E D M) the metal is removed by erosion caused by rapidly recurring spark discharges between the tool (cathode) and work (anode) separated by flooded dielectric fluid through a small gap (about 0.02 to 0.5 mm).

The dielectric is used to control the spark discharges, to help in the movement of the sparks and to act as coolant. The tool is made of cast iron, brass, copper and copper tungsten alloy. The electro discharge machining can machine hardest material and produces high degree of surface finish.

OBJECTIVE TYPE QUESTIONS

1. In orthogonal cutting of metals,
   (a) the cutting edge of the tool is perpendicular to the direction of tool travel
   (b) the cutting forces occur in two directions only
   (c) the cutting edge is wider than the depth of cut
   (d) all of the above
2. In an orthogonal cutting, the depth of cut is halved and the feed rate is double. If the chip thickness ratio is unaffected with the changed cutting conditions, the actual chip thickness will be
   (a) doubled (b) halved (c) quadrupled (d) unchanged
3. In oblique cutting of metals, the cutting edge of the tool is
   (a) perpendicular to the workpiece (b) perpendicular to the direction of tool travel
   (c) parallel to the direction of tool travel
   (d) inclined at an angle less than 90° to the direction of tool travel

4. Discontinuous chips are formed during machining of
   (a) brittle metals (b) ductile metals (c) hard metals (d) soft metals
5. The ductile materials, during machining, produce
   (a) continuous chips (b) discontinuous chips
   (c) continuous chips with built up edge (d) either (a) or (c)
6. Continuous chips with built up edge are formed during machining of
   (a) brittle metals (b) ductile metals (c) hard metals (d) soft metals
7. The factor responsible for the formation of discontinuous chips is
   (a) low cutting speed and large rake angle (b) low cutting speed and small rake angle
   (c) high cutting speed and large rake angle (d) high cutting speed and small rake angle
8. The high cutting speed and large rake angle of the tool will result in the formation of
   (a) continuous chips (b) discontinuous chip
   (c) continuous chips with built up edge (d) none of these
9. The factor responsible for the formation of continuous chips with built up edge is
   (a) low cutting speed and large rake angle (b) low cutting speed and small rake angle
   (c) high cutting speed and large rake angle (d) high cutting speed and small rake angle
10. In continuous chip cutting, the maximum heat is taken by the cutting tool.
    (a) Yes (b) No
11. In continuous chip cutting, the maximum heat.............the velocity of cutting.
    (a) depends upon (b) does not depend upon
12. The continuous chips are in the form of long coils having the same thickness throughout.
    (a) Agree (b) Disagree
13. In oblique cutting system, the maximum chip thickness
    (a) occurs at the middle (b) may not occur at the middle
    (c) depends upon the material of the tool (d) depends upon the geometry of the tool
14. In oblique cutting system, the cutting edge of the tool
    (a) may clear the width of the workpiece
    (b) may or may not clear the width of the workpiece
    (c) may not clear the width of the workpiece
    (d) should always clear the width of the workpiece
15. Which of the following statement is correct for orthogonal cutting system?
    (a) The cutting edge of the tool is perpendicular to the direction of tool travel.
    (b) The cutting edge clears the width of the workpiece on either ends.
    (c) The chip flows over the tool face and the direction of the chip flow velocity is normal to the cutting edge.
    (d) all of the above
16. In orthogonal cutting system, the maximum chip thickness occurs at the middle.
    (a) Correct (b) Incorrect

186. (c)	187. (d)	188. (a)	189. (b)	190. (c)	191. (c)
192. (b)	193. (c)	194. (d)	195. (a)	196. (a)	197. (d)
198. (c)	199. (d)	200. (a)	201. (d)	202. (a)	203. (c)
204. (b)	205. (a)	206. (d)	207. (a)	208. (b)	209. (b)
210. (c)	211. (c)	212. (b)	213. (b)	214. (a)	215. (b)
216. (c)	217. (a)	218. (c)	219. (b)	220. (b)	221. (b)
222. (b)	223. (b)	224. (c)	225. (a)	226. (a)	227. (a)
228. (c)	229. (a)	230. (b)	231. (d)	232. (c)	233. (b)
234. (c)	235. (c)	236. (b)	237. (a)	238. (c)	239. (b)
240. (c)	241. (d)	242. (a)	243. (b)	244. (a)	245. (a)
246. (b)	247. (d)	248. (c)	249. (c)	250. (c)	251. (b)
252. (b)	253. (a)	254. (b)	255. (d)	256. (d)	257. (c)
258. (a)	259. (c)	260. (a), (b)	261. (a)	262. (b)	263. (a)
264. (a)	265. (d)	266. (b)	267. (a)	268. (b)	269. (a)
270. (a)	271. (c)	272. (b)	273. (d)	274. (c)	275. (a)
276. (b)	277. (a)	278. (a)	279. (b)	280. (b)	281. (c)
282. (a)	283. (c)	284. (a)	285. (b)	286. (c)	287. (a)
288. (d)	289. (b)	290. (b)	291. (c)	292. (a)	293. (d)
294. (b)	295. (c)	296. (b)	297. (a)	298. (b)	299. (a)
300. (b)	301. (b)	302. (a)	303. (d)	304. (d)	305. (a)
306. (b)	307. (c)	308. (a)	309. (a)	310. (b), (d)	311. (a), (c)
312. (c)	313. (a)	314. (d)	315. (d)	316. (d)	317. (b)
318. (b)	319. (b)	320. (a)	321. (d)	322. (d)	323. (d)
324. (c)	325. (c)	326. (a)	327. (b)	328. (b)	329. (a)
330. (a)	331. (d)	332. (d)	333. (c)	334. (c)	335. (a)
336. (a)	337. (b)	338. (d)	339. (a)	340. (a)	341. (c)
342. (c)	343. (d)	344. (b)	345. (c)	346. (a)	347. (c)
348. (a)	349. (b)	350. (a)	351. (d)	352. (a)	353. (b)
354. (b)	355. (b)	356. (b)	357. (d)	358. (d)	359. (d)
360. (b)	361. (a)	362. (b)	363. (b)	364. (b)	365. (a)
366. (a)	367. (c)	368. (c)	369. (c)	370. (d)	371. (a)
372. (a)	373. (b)	374. (b)	375. (c)	376. (d)	377. (a)
378. (b)	379. (a)	380. (b)	381. (a)	382. (b)	383. (d)
384. (c)	385. (a)	386. (d)	387. (d)	388. (a)	389. (c)
390. (d)	391. (c)	392. (d)	393. (d)	394. (c)	395. (d)
396. (a)	397. (d)	398. (d)	399. (a)	400. (a)	401. (b)
402. (d)	403. (a)	404. (b)	405. (d)	406. (d)	407. (c)
408. (c)	409. (d)	410. (d)	411. (a)	412. (d)	413. (d)
414. (d)	415. (c)				

16

Industrial Engineering and Production Management

16.1 Introduction

The industrial engineering is an engineering approach to the detailed analysis of the use and cost of the resources of an organisation. The main resources are men, money, materials, equipment and machinery. An industrial engineer carries out such analysis in order to achieve the objectives (to increase productivity or profits etc.) and policies of the organisation.

The production management deals with the design of the production system (which includes product, process, plant, equipment etc.) and development of the control system to manage inventories, product quality, production schedules and productivity.

16.2 Work Study

The work study consists of two techniques namaly method study and work measurement. The pioneer work in this field was done by F. W. Taylor and Frank B. Gilbreth.

The *method study* is a technique to simplify the job and develop more economical methods of doing it.

The work measurement is concerned with the elimination of ineffective time (the time during which no productive work is being performed) and establishment of time standards for a job.

The objectives of method study are as follows:

1. To improve the total performance of the operating unit.
2. To maintain performance at the highest level during any given time and continuously to improve on that level.

The method study can be applied to almost all types of work, whether it be a factory, clerical or any other type of activity. The following is the basic procedure in the application of method study:

(*a*) Select the job or process to be studied.

(*b*) Record all facts about the present method by direct observation.

(*c*) Examine these facts critically.

(*d*) Develop the most practical, economic and effective method.

(*e*) Install the new developed method as a standard practice.

(*f*) Maintain the standard practice by regular routine checks.

The success of method study depends on the accuracy with which the facts are recorded.

16.3 Symbols Used in Work Study

The work study is done by means of a stop watch. In work study, all the activities are broken down into five basic types of events and each is represented by a symbol, as follows:

(*a*) ○ *Operation:* It involves a change in the location or condition of a product

(b) □ *Inspection*: It is an act of checking for correctness of the quantity or quality of the items.

(c) ⇨ *Transport*: It indicates the movement of an item from one location to another.

(d) D *Delay*: It occurs when something stops the process and a product waits for the next event.

(e) ▽ *Storage*: It represents a stage when a finished good or raw material awaits an action or when an item has been retained for quite some time for reference purposes.

16.4 String Diagram

The string diagram is used

(a) for checking the relative values of various layouts,

(b) where group of workers are working at a place, and

(c) where processes require the operator to be moved from one work place to other.

16.5 Work Measurement

The work measurement is the application of techniques to establish the time for a qualified worker to carry out a specified work at a defined level of performance. The objectives of work measurement are as follows:

(a) To plan and schedule of production,

(b) To formulate a proper incentive scheme, and

(c) To estimate the selling prices and delivery dates.

The principal techniques used to measure work are

(a) Time study,

(b) Predetermined motion time system (PMTS),

(c) Analytical estimating, and

(d) Activity (work) sampling.

16.6 Time Study

The general procedure followed in systematic carrying out the time study is as follows:

1. Select the work to be studied.
2. Record all the informations about the work, operator and surrounding conditions.
3. Break down the each operation into small elements.
4. Examine each element to ensure that the most effective method and motions are used.
5. Measure with a stop watch, the time taken by the operator to perform each element.
6. Assess the effective speed of the operator performance, *i.e.* rating factor.
7. Apply rating factor to the observed time to get basic or normal time.
8. Determine the allowances to be made.
9. Compile standard time.

Notes: (a) The *standard time* or *allowed time* is the total time in which a job should be completed at standard performance. It is obtained by adding all allowances to the basic time or normal time.

(b) The average of times recorded by a work study man for an operation is called *representative time*.

(c) The actual time read from a stop watch during time study is known as *observed time*.

(d) The assessment of performance of the operator by the time study man is known as *rating factor*.

16.7 Pre-determined Motion Time System (P.M.T.S.)

It is the work measurement technique to build up time for manual work making use of pre-determined elemental motion times. The following are the few methods of P. M. T. S.

(a) Method Time Measurement (M. T. M.)

(b) Work Factor System (W. F. S.)

(c) Basic Motion Time Study (B. M. T. S.)

(d) Motion Time Analysis (M. T. A.)

16.8 Micromotion Study

The micromotion study was originated by Frank B. Gilbreth. The study is based on the idea of dividing human activity into division of movements, known as *Therbligs*. It is the name given to the micromotion of an operation.

The study consists of analysing a motion picture taken during the performance of work. The time taken for each fundamental motion is accurately indicated in the film by a timing device. The purpose of micromotion study is to assist in finding out the most efficient way of doing work. It also train the individual operator regarding the motion economy principles and help in collecting the motion time data for synthetic time standards.

16.9 Break-even Analysis

The break-even analysis consists of total cost (*i.e.* fixed cost and variable cost) and sales revenue. The fixed costs do not increase or decrease with the sales or production such as rent, insurance, salaries etc. The variable costs increase or decrease with the sales or production such as raw material, direct labour, indirect material etc. The point at which a business neither makes a profit nor incurs a loss, is known as *break even point*. It is a point when sales revenue and total cost lines intersect.

16.10 Wage Incentive Plans

Following are the various wage incentive plans.

1. *Straight piece work system*. In this system, the worker is paid at a specified piece rate, for the number of pieces or units produced by him. The standard output is set and the worker is guaranteed a minimum wage. Thus, if a worker produces less than the standard output, he will get the minimum guaranteed wage. If another worker produces more than standard output, he is paid a wage in direct proportion to the number of pieces produced by him at the specified piece rate.

2. *Halsey plan*. In this system, a standard time is set from past production records for the completion of a job. The worker is guaranteed a minimum wage. If a worker completes the job in the standard or more than the standard time, he is paid at his guaranteed time rate. If a worker completes the job in less than standard time, he is paid a bonus in addition to his base wage at the guaranteed time rate. The amount of bonus varies from 30 to 50 percent of the time saved. If R is the base rate guaranteed per hour, S is the standard time for the job and T is the actual time, then according to Halsey 50-50 plan, the wages for the job will be

$$E = T.R + \frac{S - T}{2} \times R$$

3. *Rowan plan*. In this system, an hourly rate is guaranteed, standard time for the completion of job is established from the past production record. If the job is completed in the standard or more

than the standard time, the worker is paid the guaranteed wage. If the job is completed in less than the standard time, the worker is paid a bonus in addition to the guaranteed wage.

According to Rowan plan system, the total earning of the work or wages for the job is given by

$$E = T.R + \frac{S - T}{S} \times R$$

4. *Gantt plan.* In this system, output standard for a given time (standard task level) is set by a careful scientific study of the work. If a worker reaches the standard task level, he is paid a bonus which is usually one-third of task rate. If the worker fails to reach the set standard, he is paid only the guaranteed wage.

5. *Emerson's efficiency plan.* In this system, a standard time is established for each job. During each pay period, the number of hours taken by each worker to complete the job is recorded. The efficiency of each worker is calculated which is given as the ratio of the standard time for the job to the time taken by the worker.

The worker is guaranteed his time rate. The work standard is set at a high level. If the efficiency is $66\frac{2}{3}$ % or below, then the worker is paid his guaranteed wage and no bonus is paid. At 67% efficiency, the worker is paid this time rate plus a small bonus. The bonus increases with the increase in efficiency.

16.11 Terms Used in Network Planning Methods

The following terms are commonly used in network planning methods:

1. *Event.* The event is a specific instant of time which makes the start and the end of an activity. The event consumes neither time nor resources. It is represented by a circle and the event number is written within the circle, as shown in Fig. 16.1.

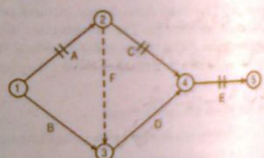


Fig. 16.1

2. *Activity.* Every project consists of a number of job operations or tasks which are called activities. An activity is shown by an arrow and it begins and ends with an event. An activity consumes time and resources. An activity may be performed by an individual or a group of individuals.

The activity may be classified as critical activity, non-critical activity and dummy activity. The activity is called critical if its earliest start time (E.S.T.) plus the time taken by it, is equal to the latest finishing time (L.F.T.). A critical activity (*e.g.* A, C or E) is marked either by a thick arrow or by two lines as shown in Fig. 16.1.

The non-critical activities have provision (float or slack) so that, even if they consume a specified time over and above the estimated time, the project will not be delayed. In Fig. 16.1, B and D are non-critical activities.

When two activities start at the same instant of times (like activities C and D), the head events are joined by a dotted arrow and this is known as dummy activity as shown by F in Fig. 16.1. The dummy activity does not consume time and resources.

3. *Critical path.* It is that sequence of activities which decide the total project duration. It is formed by critical activities. In Fig. 16.1, 1-2-4-5 is the critical path. A critical path consumes maximum resources. It is the longest path and consumes maximum time. A critical path has zero float or slack.

4. *Slack or Float.* The slack is with reference to an event and float is with respect to an activity. In other words, slack is used with PERT and float with C.P.M., but in general practice, they may be used interchangeably. The slack represents the difference between the earliest completion or finish time and the latest allowable time. The slack may be positive, negative or zero.

When the slack of an activity is positive, then it represents a situation where extra resources are available and the completion of project is not delayed.

When the slack of an activity is negative, then it represents that a programme falls behind schedule and additional resources are required to complete the project in time.

When the slack of an activity is zero, then the activity is critical and any delay in its performance will delay the completion of whole project.

16.12 Programme Evaluation Review Technique (PERT)

The programme evaluation review technique (PERT) is a project planning and control technique. It is an event oriented technique. It provides an approach for keeping planning up-to-date. It provides a way for management to require that planning be done on a uniform and logical basis. It permits management to foresee quickly the impact of variations from the plan. The programme evaluation review technique is applied for long-range planning, installation of machinery, research and development of products and marketing programmes and advertising programmes. The PERT analysis is based upon the following three time estimates :

(*a*) *Optimistic time.* It is the shortest possible time in which an activity can be completed if every thing goes exceptionally well.

(*b*) *Most likely time.* It is the time in which the activity is normally expected to complete under normal contingencies.

(*c*) *Pessimistic time.* It is the time which an activity will take to complete in case of difficulty. It is the longest of all the three time estimates.

If
t_o = Optimistic time,
t_n = Most likely time, and
t_p = Pessimistic time.

Then the probabilistic time (t_m) for completion of an activity is given by

$$t_m = \frac{t_o + t_p + 4t_n}{6}$$

16.13 Critical Path Method (CPM)

The critical path method (CPM) was first used by Morgan R. Walker in 1957. It helps in ascertaining time schedules, makes better and detailed planning possible, encourages discipline and provides a standard method for communicating project plans schedules and to time and cost performance.

16.14 Organisation

The organisation is a group of people which works under an executive leadership. It divides the work and responsibilities of the employees. It establishes a relationship between authority and responsibility and controls the efforts of groups. The organisation is a step towards the achievement of established goals. The following are the various types of organisations :

1. *Line organisation.* It is also called military type of organisation because it resembles to olden military organisation. Sometimes it is also called as the scalar type since it has straight flow of authority within a single unit. It is the simplest form of organisation in which responsibility of each

individual is fixed, discipline is strong and quicker decisions are taken. The disadvantage of this organisation is that it overloads a few key executives and encourages dictatorial way of working.

The line organisation is suitable for small concerns and for automatic and continuous process industries such as sugar, paper, oil refining, spinning and weaving industries.

2. *Functional organisation.* This type of organisation was introduced by F.W. Taylor. In the functional organisation, the quality of work is better, wastage of material is minimum and specialised knowledge and guidance to individual worker is provided. Through this type of organisation is obsolete now-a-days, yet in the modified form, it is frequently used in some most modern and advanced concerns.

3. *Line and staff organisation.* This type of organisation possesses practically all the advantages of both the line and functional organisations. In the line and staff organisation, the quality of work is improved, and there is less wastage of material, man and machine hours. The expert advice from specialist staff executives can be made use of. This type of organisation is preferred for an automobile industry.

4. *Line, staff and functional organisation.* This type of organisation has many of the advantages of line and staff organisation and functional organisation. This type of organisation is preferred for a steel industry.

16.15 Inventory Control

The most important functions of inventory (stock) control are as follows :

1. to have good stock control system.
2. to have technical responsibility for the state of materials.
3. to run the stores effectively.

In inventory control, the economic ordering quantity (EOQ) is obtained by the quantity whose procurement cost is equal to inventory carrying cost.

If A is the total items consumed per year, P is the procurement cost per order and C is the annual inventory carrying cost per item, then the most economic ordering quantity is given by

$$EOQ = \sqrt{\frac{2\,A.P}{C}}$$

16.16 Plant Layout

The plant layout is the physical arrangement of buildings, machinery, equipments, work places and other facilities of production in order to process the product in the most efficient manner.

According to Muther, the basic principles of best layout are integration, minimum movements and material handling, smooth and continuous flow, safe and improved environment and flexibility.

Following are the three types of plant layout :

1. *Process layout.* The process layout is also known as functional layout or analytical layout. This type of layout is employed where

   (*a*) low volume of production is required,

   (*b*) similar jobs are manufactured on similar machines, and

   (*c*) machines are arranged on functional basis.

The process layout has the following drawbacks :

(*a*) More floor space is required.

(*b*) Production control is more difficult and costly.

(*c*) Routing and scheduling is more difficult.

(*d*) handling and back-tracking of materials is too much.

2. *Product layout.* The product layout is also known as *synthetic layout*. This type of layout is best suited where one type of product is produced and the product is standardised. It is used for mass production of the product. The product layout lowers overall manufacturing time, requires less space for placing machines and utilises machine and labour better. In the product layout, specialised and strict supervision is required and machines cannot be used to their maximum capacity. The manufacturing cost rises with a fall in the volume of production.

The product layout is suitable for automobile manufacturing concern.

3. *Fixed position layout.* The fixed position layout is also known as *static product layout*. In this type of layout, the product is so large that it cannot be moved from one location to another location, but tools, material and labour are moved to the product to perform specific operations. This type of layout is used for manufacturing ships, aeroplanes, steam turbines etc.

16.17 Routing, Scheduling and Dispatching

The *routing* is a vital portion of production control. It lays down the flow of work in the plant. It determines how and where the work is to be done, what machines are to be used and it prescribes the path and sequence of operations to be followed. This provides a basis for scheduling, despatching and control functions.

The *scheduling* may be called as the time phase of loading. The loading means the assignment of work to a facility (man, machine, group of men, group of machines) where as scheduling includes, in addition, the specifications of time and sequence in which the work is to be done.

The *dispatching* is the most important activity of the production, planning and control. It is defined as the physical release of work authorisation to a operating facility (men, machine) in accordance with a previously established plan developed by routing and scheduling functions.

16.18 Linear Programming

The linear programming is one of the classical operations research technique. It is defined as the mathematical technique for finding the best use of limited resources of a company in the maximum manner. In can be applied successfully to chemical industry, oil industry, iron and steel industry and banks.

The simplex procedure is an excellent technique for solving linear programming problems.

OBJECTIVE TYPE QUESTIONS

1. Work study involues

   (*a*) only method study (*b*) only work measurement

   (*c*) method study and work measurement (*d*) only motion study

2. Work study is mainly aimed at

   (*a*) determining the most efficient method of performing a job

   (*b*) establishing the minimum time of completion of a job

   (*c*) developing the standard method and standard time of a job

   (*d*) economising the motions involved on the part of the worker while performing a job

3. The work study is done by means of

   (*a*) planning chart (*b*) process chart

   (*c*) stop watch (*d*) any one of these

36. (b)	37. (c)	38. (a)	39. (a)	40. (a)	41. (d)
42. (c)	43. (b)	44. (a)	45. (b)	46. (b)	47. (d)
48. (c)	49. (a)	50. (c)	51. (c)	52. (b)	53. (b)
54. (d)	55. (a), (b)	56. (d)	57. (a)	58. (c)	59. (d)
60. (c)	61. (b)	62. (a)	63. (d)	64. (a)	65. (a)
66. (b)	67. (a)	68. (c)	69. (d)	70. (d)	71. (d)
72. (a)	73. (a)	74. (a)	75. (a)	76. (d)	77. (d)
78. (b)	79. (a)	80. (d)	81. (a)	82. (b)	83. (d)
84. (a)	85. (c)	86. (c)	87. (d)	88. (d)	89. (c)
90. (c)	91. (a)	92. (d)	93. (a)	94. (b)	95. (c)
96. (c)	97. (d)	98. (a)	99. (d)	100. (b)	101. (d)
102. (c)	103. (d)	104. (d)	105. (b)	106. (d)	107. (c)
108. (d)	109. (a)	110. (c)	111. (c)	112. (d)	113. (b)
114. (d)	115. (d)	116. (c)	117. (d)	118. (a)	119. (d)
120. (d)	121. (b)	122. (a)	123. (d)	124. (d)	125. (a)
126. (c)	127. (c)	128. (d)	129. (b)	130. (C), (A), (D), (B)	
131. (a)	132. (a)	133. (a)	134. (a)	135. (c)	136. (d)
137. (d)	138. (d)	139. (b)	140. (a)	141. (a)	142. (a)
143. (d)	144. (d)	145. (d)	146. (b)	147. (a)	148. (c)
149. (b)	150. (d)	151. (a)	152. (c)	153. (d)	154. (a)
155. (a)	156. (a)	157. (b)	158. (c)	159. (d)	160. (b)
161. (c)	162. (c)	163. (c)	164. (d)	165. (c)	166. (b)
167. (a)	168. (d)	169. (b)	170. (d)	171. (c)	172. (d)
173. (a)	174. (c)	175. (c)			

17

Automobile Engineering

17.1 Introduction

An automobile (also called automotive) is a self-propelled vehicle which is used for the transportation of passengers and goods on the ground. A self-propelled vehicle is that in which power is produced within itself for its propulsion. The various types of self-propelled vehicles are scooters, motor cycles, cars, buses, trucks, tractors, locomotives, motor boats, ships, aeroplanes, helicopters, rockets, etc. Since an automobile is propelled on the ground only, therefore, it differs from other self-propelled vehicles like aeroplane, ship, locomotive, motor boat etc.

An automobile is a combination of a large number of parts. It can be divided into two major constituents *i.e.* body and the chassis. The body is that part where passengers have their seats or the luggage and cargo to be carried is placed. The chassis is the main machine portion which have constituents like frame, wheels, axles, engine, steering, fuel tank, radiator etc.

In general, an automobile, is made up of the following components :

(*a*) Basic structure or frame work ; (*b*) Engine or source of power ; (*c*) Transmission system ; (*d*) Body or super structure ; (*e*) Auxiliaries ; and (*f*) Controls.

The basic body structure of automobiles is of two types :

(*a*) Body and frame type; and (*b*) Unit type (frameless structure also known as monocoque body).

In the *body and frame type* design, the body is bolted to a separate frame. Most of the suspension, bumper and brake loads are transmitted to the frame. In the *unit type* design, the sheet metal parts are welded together, forming a framework to which an outer skin is attached. In other words, the chassis is integral with the body. This type of design enables reduction in body weight, and consequently improves the fuel consumption and makes driving easy. It also increases the safety levels because of better impact absorption.

17.2 Performance of Automobile

The pressure developed by the burning of fuel in the engine cylinder is transmitted to the crankshaft by the piston and connecting rod and a turning force or effort known as *torque* is produced. The crankshaft is coupled to the driving road wheels through clutch, gear box, propeller shaft, differential and axle shafts in an automobile. Thus, torque produced by the engine is transmitted through the drive line to the road wheels to propel the vehicle. The torque depends upon the pressure exerted on the piston and the length of crank arm and it is measured in newton-metre (N-m). The actual power delivered by the engine is known as brake power (B.P.)* and it is measured in watts (W) or kilowatts (kW).

The torque increases with the increase in engine speed up to a certain point after which it starts to fall down even though the engine speed continues to increase. The number of revolutions per minute (r.p.m.) at which the torque begins to decrease, depends upon the engine design. At higher speeds, engine vacuum falls down and less fuel enters the cylinder resulting in lesser force available

* The power actually developed by the engine cylinder is known as *indicated power* (I.P.). The mechanical efficiency is the ratio of brake power (B.P.) to the indicated power (I.P.).

at the piston and thus there is a fall in torque. The power and torque curve of a particular petrol engine with respect to engine speed is shown in Fig. 17.1.

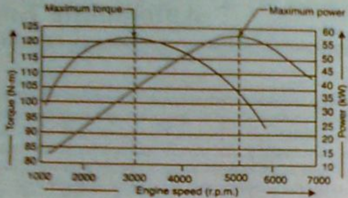


Fig. 17.1

The torque available at the contact between driving wheels and road is known as *tractive effort*. The gearbox and final drive at differential act as leverage to multiply torque which is inversely proportional to the speed. If the gear speed is lowered, the torque shall be increased in the same ratio and vice-versa. Thus, the torque at the driving wheels,

$$T_W = G \times \eta_t \times T_E$$

where G = Overall gear ratio = Gear box gear ratio × Final drive ratio,

η_t = Overall transmission efficiency, and

T_E = Mean engine torque in N-m.

We know that, engine torque,

$$T_E = \frac{60 \times B.P.}{2\pi N}$$

where N = R.P.M. of the crankshaft, and

$B.P.$ = Brake power in watts.

Since the torque at the driving wheels acts through the radius of wheel, therefore, the tractive effort,

$$F = \frac{T_W}{r} = \frac{G \times \eta_t \times T_E}{r} = \frac{G \times \eta_t \times B.P. \times 60}{2\pi N \times r}$$

It may be noted that the ratio between the engine r.p.m. and the vehicle speed depends upon the overall gear ratio. A vehicle having four speed gearbox shall have four different speeds and the ratio between the engine *r.p.m.* and the vehicle speed shall be different. Thus, R.P.M. of the driving wheel,

$$N_T = \frac{60 \times V}{2\pi r} \qquad \text{...}(i)$$

where V = Vehicle speed in m / s, and

r = Radius of the driving wheel in metres.

We also know that, R.P.M. of the driving wheel,

$$N_t = \frac{\text{Crankshaft R.P.M.}}{\text{Overall gear ratio}} = \frac{N}{G} \qquad \text{...}(ii)$$

From equations (*i*) and (*ii*),

$$\frac{60 \times V}{2\pi r} = \frac{N}{G} \quad \text{or} \quad \frac{V}{N} = \frac{2\pi r}{60\,G}$$

From the above, we see that engine torque can be increased by reduction gearing. The torque transmitted by the engine through gearbox and propeller shaft to the final drive is increased in every gear speed except in top (direct) and overdrive. The torque transmitted by propeller shaft is further increased by means of gear reduction of final drive (drive pinion and ring gear at differential). The torque of final drive, provided a differential is fitted, is always equally divided between each axle shaft irrespective of speed of road wheel, although this does not apply to limited-slip type differential.

17.3 Resistances to a Moving Vehicle

The thrust known as *tractive effort* provided by the engine at the driving wheels varies at different engine speeds and gear positions. A moving vehicle is opposed by the various forces known as *resistances*. In order to keep the vehicle moving, tractive effort equal to the sum of all the opposite forces has to be applied to it. If the tractive effort exceeds the sum of all the resistances, the excess tractive effort will accelerate the vehicle, but if the tractive effort is less than the sum of all the resistances, it will decelerate the vehicle. Following are the main forces, which opposes the motion of the vehicles :

1. *Rolling resistance*. The rolling resistance is mainly due to the friction between the wheel tyre and the road surface. It mainly depends upon the load on each road wheel, type of tyre tread, wheel inflation pressure and type of road surface. Mathematically, rolling resistance,

$$R_r = K.W$$

where K = Constant of the rolling resistance, and

W = Weight of the vehicle in newtons.

The value of K for best roads and loose sandy roads is generally taken as 0.0095 and 0.18 respectively.

2. *Wind or air resistance*. The wind or air resistance depends upon the shape and size of vehicle body, air velocity and speed of the vehicle. It increases as the square of vehicle speed owing to which much importance is given to streamlining and frontal area of modern automobiles. When calculating air resistance, air velocity is usually neglected. Mathematically, air resistance,

$$R_a = (0.5\,\rho.\,c_d)\,A.\,V^2$$

where ρ = Air density in kg/m^3,

c_d = Coefficient of drag,

A = Projected frontal area in m^2, and

V = Vehicle speed in m/s.

Generally, for calculating air resistance, it is easy to take the value of vehicle speed (V) in km / h. Thus, air resistance,

$$R_a = (0.0386\,\rho.\,c_d)\,A V^2 = K_a\,A\,V^2 \qquad \text{...}(K_a = 0.0386\,\rho.\,c_d)$$

where K_a = Coefficient of air resistance,

A = Projected frontal area in m^2, and

V = Vehicle speed in km / h.

It may be noted that since the air resistance increases with the square of speed, thus at twice the speed, the air resistance is 4 times. For best streamlined cars, coefficient of air resistance (K_a) is 0.023, for average cars, K_a = 0.031 and for buses and trucks, K_a = 0.045.

3. *Gradient resistance*. The gradient resistance is due to the steepness of road gradient. It depends upon the vehicle weight and the road gradient. Mathematically, gradient resistance,

$$R_g = W \sin\theta$$

where W = Weight of the vehicle in newtons, and

θ = Inclination or gradient of road.

It may be noted that when the vehicle is moving along a level road, it has to face rolling and air resistance. When the vehicle moves up the gradient, it has to encounter the gradient resistance in addition to the rolling and air resistances.

The power required to propel a vehicle is proportional to the total resistance to its motion and speed. Mathematically, power required (in watts) to propel a vehicle is given by

$$P_v = R \times V \quad \text{... (Neglecting transmission losses)}$$

$$= \frac{R \times V}{\eta_t} \quad \text{... (Considering transmission losses)}$$

where R = Total resistance in newtons,

V = Vehicle speed in m / s, and

η_t = Transmission efficiency.

17.4 Internal Combustion Engines

The internal combustion (I.C.)* engines are employed in automobiles. In order to run these engines, the air-fuel mixture burns in the engine cylinder to develop power. Following are the two types of I.C. engines which are commonly used in automobiles :

1. *Petrol engines (Spark ignition engines).* In petrol engines, the air and fuel (petrol) mixture is drawn during the suction stroke. The mixture is compressed to approximately 20 to 30 bar (compression ratio, 6 to 10) in the compression stroke, thus raising the temperature in the range of 400 to 500°C. The temperature reached after compression is below the auto-ignition threshold of the air fuel mixture and thus it is ignited with the help of a spark plug before the piston reaches the top dead centre.

The petrol engine works on Otto cycle (also known as constant volume cycle). In Otto cycle, combustion takes place at constant volume, as whole of the fuel is burned instantaneously as an explosion.

2. *Diesel engines (Compression ignition engines).* In diesel engines, the air is drawn during the suction stroke, which is compressed to approximately 30 to 45 bar (compression ratio, 14 to 25), thus raising the air temperature in the range of 700 to 900°C. Into this glowing hot air, the fuel (diesel) is injected through a nozzle and finely dispersed. It evaporates, mixes with air and ignites spontaneously. During combustion, the pressure increases in the range of 55 to 75 bar. The burned gases, under full load, are at a temperature of about 600°C but in case of petrol engines it is 900°C. Thus, it may be noted that diesel engine utilizes the heat of the fuel to a better degree and for this reason its fuel consumption is lower.

The diesel engine works on diesel cycle (also known as constant pressure cycle). In diesel cycle, the combustion takes place at constant pressure because burning takes place gradually, without an explosion as the fuel enters.

17.5 Parts of an I.C. Engine

The main parts of an I.C. engine as shown in Fig. 17.2, are discussed below:

1. *Cylinder head.* The cylinder head forms a part of the combustion chamber and is subjected to high temperatures and pressures. It requires to have good heat conduction and be readily cooled. These are generally made of aluminium alloy, but there are also some cast iron cylinder heads. Aluminium alloy cylinder heads use seat rings in the valve seats, and for the exhaust valves, these are often made with better heat resistance than those for the inlet valves.

2. *Cylinder head gasket.* The cylinder head gasket is designed to prevent the combustion gases from leaking from the joint between cylinder block and cylinder head. It should be resistant to pressures and heat, and should be compressible by an appropriate amount. The main types of cylinder

* I.C. engines, are dealt in Chapter 8 also.

head gasket are of metal, made from a single soft steel plate. The most commonly used compound cylinder head gaskets are metal asbestos gaskets, wire woven gaskets and metal graphite gaskets.

3. *Cylinder and cylinder block.* The cylinder and cylinder block are normally cast as a single unit, but sometimes cylinder liners are inserted into the cylinder blocks, which can be replaced when worn out. The inside of each cylinder liner is given a fine crosshatch pattern through a machining process known as *honing*. In order to reduce friction and wear on the cylinder from the sliding movement of the piston, the piston is ground to a very fine finish. The material used for the cylinder block is grey cast iron or aluminium alloy. It may be noted that the cylinder block is the foundation of the engine. The other engine parts are attached or assembled into the cylinder block.

The internal diameter of a cylinder is referred to as either *cylinder bore* or simply *bore*. The engine's displacement is determined by the bore, the piston stroke (*i.e.* the distance that the piston travels between TDC and BDC), and the number of cylinders employed. In a multi-cylinder engine, the distance between the centres of adjacent bores is known as the *bore pitch*. The distance from the cylinder top surface to the crankshaft's centreline is called the *block height*. (This is same in case of V-type engine also).

4. *Piston.* The main function of a piston is to transmit the force exerted by the burning of charge to the connecting rod. Since the pistons move backwards and forward under high temperatures and pressures, therefore, they should have very good heat conduction and wear resistance, and should be of lightweight. The material used for pistons are aluminium alloys made from aluminium with copper, silicon, nickel etc.

5. *Piston rings.* The piston rings are housed in circumferential grooves provided on the outer surface of the piston. The piston rings must be resistant to wear, tough, resistant to heat, and be able to hold oil. Generally, there are two sets of rings, compression rings and oil control rings. The compression rings are made from a special cast iron or carbon steel. The primary function of compression rings is to form a gas tight seal between the piston and the inner wall of the cylinder, while at the same

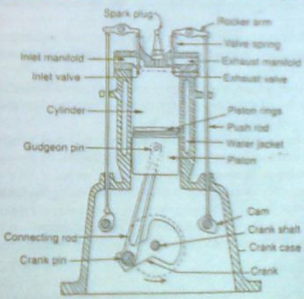


Fig. 17.2

time transmitting the heat to the cylinder that the piston receives during combustion. The *oil control rings* are made from carbon steel and their function is to provide effective seal to prevent leakage of the oil into the engine cylinder.

6. *Connecting rod.* It is a link between the piston and crankshaft. The main function of the

connecting rod is to transmit force from the piston to the crankshaft. Moreover, it converts reciprocating motion of the piston into the circular motion of the crankshaft, in the working stroke. Since the piston moves vertically while the crankshaft rotates, therefore, the connecting rod is subjected to a combination of axial and bending stresses. Consequently, the connecting rod must be light and rigid as possible.

The upper (*i.e.* smaller) end of the connecting rod is fitted to the piston by the piston pin and the lower (*i.e.* bigger) end to the journal of crankshaft. The connecting rods are die-forged from special steels such as nickel chrome steel and chrome molybdenum steel, mechanically strenghtened, and are given an I-shaped cross-section to make the connecting rod light itself.

7. *Crankshaft.* The function of a crankshaft is to convert reciprocating motion of the piston (due to combustion of air-fuel mixture) into the rotary motion with the help of a connecting rod. It consists of crank pins, webs (crank arms or cheeks), balancing weights and main journals. The crankshaft is supported by the main bearings on the main journals. The balancing weights are provided on the opposite side of the crank arms for balancing. Since the crankshaft rotates at high speeds under heavy loads, therefore it must have good strength, and wear resistance. It must have both static and dynamic balance, and must be able to rotate smoothly.

The number of main bearings depend upon the design of the engine and the number of cylinders. It may be noted that more the number of main bearings, less is the possibility of vibration and distortion of the crankshaft of a given size. In order to reduce vibration in the engine, the crankshaft and flywheel are balanced separately. The balancing is necessary to prevent severe damage to the engine, especially to the bearings.

The crankshaft is generally made from carbon steel, special steel, or special cast iron. The crankshaft may be forged or cast, but the former method is more common. After die forging, the shaft is machined mechanically, and to improve wear resistance, the surfaces of journals and crankpins are generally hardened by carburising and then ground.

8. *Valve mechanism.* Since the valves are subjected to high working temperatures, therefore, they must have good heat conduction, heat resistance, corrosion resistance, wear resistance and shock resistance.

The material for inlet valves is usually a special carbon steel including silicon and chrome. This has particular good corrosion resistance, and also has good heat conduction and a low coefficient of expansion.

The exhaust valves are subjected to high temperatures, so the material used for exhaust valves is a special steel made by including chrome and nickel in carbon steel. This alloy has particularly good heat resistance and corrosion resistance.

9. *Camshaft.* The camshaft is usually forged from special steel including nickel, chrome and molybdenum, or cast from special cast iron. The cams and journals are normally carburised or given some other surface hardening treatment to improve wear resistance.

10. *Valve springs.* The valve springs need to provide a spring force that rapidly and precisely closes the valves in accordance with the cam movement. Since they are repeatedly compressed and relaxed together with the engine speed, therefore they should be resistant to fatigue and very tough. The material is usually heat resistant spring steel, chrome vanadium steel or silicon chrome steel.

17.6 Engine Operation Cycle

The following sequences of strokes make up the operation of engine :

1. *Suction stroke.* In this stroke, a mixture of fuel -vapour in correct proportion, is supplied to the engine cylinder.

2. *Compression stroke.* In this stroke, the fuel vapour is first compressed in the engine cylinder.

3. *Expansion or working stroke.* In this stroke, the fuel-vapour is fired just before the compression is complete. It results in the sudden rise of pressure, due to expansion of the combustion products in the engine cylinder. The sudden rise of the pressure pushes the piston with a great force,

and rotates the crankshaft. The crankshaft in turn drives the gearbox connected to it.

4. *Exhaust stroke.* In this stroke, the burnt gases (or combustion products) are exhausted from the engine cylinder, so as to make space available for the fresh fuel-vapour.

Note : The above mentioned strokes are meant for gas and petrol engines. But in case of diesel engines, pure air is sucked in suction stroke which is compressed during the compression stroke. The diesel fuel is admitted into the engine cylinder (just before the beginning of the expansion stroke) and it is ignited by the hot air present in the cylinder. The expansion and exhaust strokes are similar to the gas and the petrol engines.

17.7 Two Stroke and Four Stroke Cycle Engines

In a *two stroke engine*, the working cycle is completed in two strokes of the piston or in one revolution of the crankshaft. This is achieved by carrying out the suction and compression processes in one stroke (*i.e.* in inward stroke) and the expansion and exhaust processes in the second stroke (*i.e.* in outward stroke). In a *four stroke engine*, the working cycle is completed in four strokes of the piston or in two revolutions of the crankshaft. This is achieved by carrying out suction, compression, expansion and exhaust processes in each stroke.

17.8 Fuel System

The fuel system supplies the fuel to the engine. It consists of the following parts:

(*a*) *Fuel tank.* It is used for storing the fuel.

(*b*) *Fuel gauge.* It is used to measure the quantity of fuel present in the strorage tank.

(*c*) *Fuel pump.* It is used to draw the fuel from the tank and deliver to the carburettor (or injector).

(*d*) *Carburettor* (*Throttle body*). It is a device, which mixes the air and fuel, and supply the mixture so formed, in correct proportions, for proper combustion, to the engine cylinder under all conditions of load, speed etc. Despite mixing the fuel with air in correct proportion, it also automatically provides a richer mixture (*i.e.* more fuel and less air in proportion) for starting, idling and acceleration, and a leaner mixture (*i.e.* less fuel and more air in portion) for part throttle operation. In order to accomplish all these tasks, a carburettor has a variety of fixed and adjustable jets, ports, pump and passages arranged in the systems.

In some petrol engines, electronically controlled fuel injection system is used instead of carburettor. In this system, the volume of incoming air is detected, a computer uses the information to determine the volume of fuel required to give a predetermined air-fuel (A/F) ratio, and the fuel is supplied forcefully through injectors which are located in intake manifold, just at the back of intake valve. It may be noted that in comparison to the carburetor-type fuel system, the fuel injection system has many advantages like improved fuel economy, improved emission, higher power and higher response.

Note: In petrol engines, fuel is injected during suction stroke in the air stream in intake manifold whereas in diesel engine, it is injected directly into the combustion chamber near the end of compression stroke.

17.9 Cooling System

A large amount of heat is generated with the burning of air-fuel mixture in the engine cylinder. It has been experimentally found that about 30% of the heat generated is converted into mechanical work. Out of the remaining heat (about 70%) about 40% is carried away by the exhaust gases into the atmosphere. The remaining part of the heat (about 30%), if not removed by any other means, can cause serious troubles to the engine. Thus, the purpose of cooling system is to remove this heat and keep the engine at an appropriate temperature, no matter under what conditions the automobile is running. The following two types of cooling system are used in automobile engines :

1. *Air cooling system.* This type of cooling system is mostly employed in light engines such as in motor cycles and scooters. The air cooled engines contain fins or ribs on the outer surfaces of the cylinders and cylinder heads. These fins provide more area for air contact, resulting in better radiation of heat

2. *Liquid or water cooling.* This type of cooling system consists of a radiator, water pump, water jacket, thermostat, fan and other components. Each cylinder of the engine is surrounded by a water jacket. While the engine is running, the heat generated in each cylinder is conducted through the cylinder wall and into the coolant, which is circulated inside the water jacket by the water pump. The heated coolant is then fed to the radiator, where it is cooled by air that passes through an array of cooling fins. Then, the coolant is recirculated to the engine.

A thermostat is fitted between the engine and radiator. When the engine is started from cold, the thermostat closes to prevent coolant from entering the radiator until the engine has warmed up. It may be noted that the coolant circulates only around the engine when the thermostat is closed. In case of non-closure of the thermostat, the engine would take an excessively long time to reach its optimum temperature.

It may be noted that the water is generally used as coolant to absorb and transfer heat in order to prevent overheating of the engine. Though water is a satisfactory liquid to use for absorbing and transferring heat, yet it has several drawbacks. The following are the drawbacks of using water as a coolant medium.

(*a*) It has a relatively low boiling point and freezes rapidly, thus it cannot flow around the cooling system. Furthermore, freezing increases the volume of water and this may rupture the cylinder block or other cooling system parts.

(*b*) It causes rust and scale formation inside the cooling system.

For the above reasons, some chemicals known as anti-freeze solutions are mixed with water. Ethylene glycol is considered the best anti-freeze. When mixed with water, it lowers the freezing point of water below 0°C and increases the boiling point of water above 100°C. Some inhibitors and additives are also added to the coolant (mixture) to prevent the buildup of rust and scale.

17.10 Lubricating System

It is the system by which the various rotating and sliding engine parts are lubricated to reduce friction. An oil film is formed to prevent metal parts from coming into direct contact with one another. The lubrication devices include oil pumping, filtration, cooling, circulation and oil pressure regulation.

When the engine is not running, the engine oil stays in the oil pan at the bottom of the engine. When the engine is started, oil in the pan is sucked up by the oil pump (through strainer) linked directly to the crankshaft, and its pressure is regulated by a relief valve. The oil is then filtered by the oil filter, and cooled by the oil cooler. The filtered and cooled oil is then fed separately to the cylinder head and oil galleries.

The oil pumped to the oil gallery lubricates the crankshaft journal, and is then sent through the oil paths in the crankshaft to the crank pin lubricating, the connecting rod bearings. It is ejected out from the connecting rod in form of oil jets to lubricate the cylinders and piston pins.

The flow of oil pumped to the cylinder head is regulated by oil control orifices in the cylinder block before being fed to the cam holders and rocker arm pivots. The oil fed to the holders lubricate the camshaft journals and some of the oil is ejected out in the form of jet to lubricate the cams. The oil fed to the rocker arm pivot lubricates the pivot. After all the components have been lubricated, the oil returns to the oil pan.

17.11 Transmission

The power generated in the engine of the automobile is sent to the wheels for their movement with the help of transmission. The basic functions of transmission are:

1. To transfer the engine output power to the final driven gear.
2. To provide sufficient torque at starting, ascending, accelerating, braking, etc.,

3. To provide low to high speed driving capability, and
4. To change the direction of wheel rotation (forward or reverse).

The engine rotation is transmitted to the transmission mainshaft through the action of a clutch. This mainshaft then drives a countershaft using a set of meshing gears which are selected by the gearshift lever. The countershaft's output gear transfers the motion to the differential assembly final gear, and the differential transmits it to the left and right driveshafts. These shafts ultimately turn the left and right wheels respectively.

17.12 Clutch

An automobile has to operate under varying load conditions on the road. It may be noted that when starting engines and also during gear changes, it is necessary to cut off load upon the engine. The *clutch* is a device to continue or discontinue load on the engine as necessary to solve these problems.

The clutch is installed between the engine and transmision. It transmits the power of the engine generally through the use of friction. The clutch is linked to the clutch pedal in the passenger compartment. When the driver presses down on the clutch pedal, the linkages causes the clutch to disengage. This uncouples the engine from the transmission. When the driver releases the clutch pedal, springs in the clutch causes it to engage again. Now power can flow from the engine, through the clutch, to the transmission and power train.

The main components of a clutch are engine flywheel, a friction (clutch) disc, and a pressure plate. The flywheel is connected to the engine crankshaft. When the engine is running, the flywheel is rotating. The pressure plate is attached to the flywheel and thus it also rotates. The friction disc, which is splined to transmission main shaft, is located between the two.

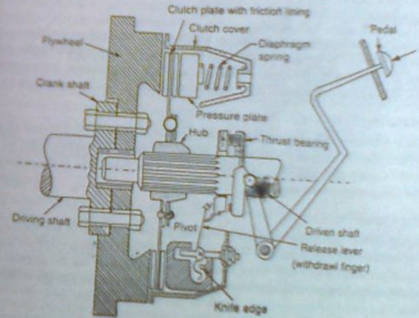


Fig. 17.3

When the clutch pedal is in the released condition (*i.e.* when the clutch is engaged), the pressure plate is pushed solidly in direction of the flywheel by the diaphragm spring, which is located inside the clutch cover. This action binds the friction disc between the two driving members. These three components then rotate as one, allowing the rotation of the engine to be transferred to the transmission as shown in Fig. 17.3.

When the driver depresses the clutch pedal (to disengage the clutch), the motion of the pedal is transferred using either hydraulic pressure or a cable to the release fork. The release fork then moves the release bearing, pushing it against the centre of the diaphragm spring. This action forces the pressure plate to move away from the friction disc. There are now air gaps between the flywheel and the friction disc, and between the friction disc and the pressure plate. No power can be transmitted through the clutch.

17.13 Automatic Transmission

The automatic transmission (briefly written as AT) allows the vehicle to automatically perform the gearshift operations in response to load, speed, and other relevant conditions. The principle components of an automatic transmission are the torque converter, the gear unit, and the hydraulic unit.

The function of the torque converter mechanism is to transfer the engine's output power to the gear unit through the action of a special fluid. However, it also operates in the complete reverse also. It may be noted that when the vehicle is stopped, it is important for the torque converter's fluid to absorb any variation in speed and not to transfer engine power in such a situation. Further, the torque converter has another important function of increasing the engine torque in a set output range.

However, it is not possile to deal adequately with all possible situations of driving using torque increases generated by the torque converter alone. For this reason, further changes to the driving force are made to the gear unit in accordance with the current driving conditions. In addition, the gear unit also implements the necessary gear changes when the vehicle is to be driven in reverse.

The hydraulic control unit converts engine load, speed, and other similar variables into hydraulic signals and controls the shifting of the gear unit in accordance with the corresponding hydraulic pressures. This component also performs control of the lock-up clutch.

17.14 Starting System

The starting (or cranking) system comprises a battery, a starter, and an ignition switch. When the ignition switch is turned to the start position, the starter begins cranking the engine using power from the battery. The starter turns the crankshaft and reciprocates the pistons in order to compress the air-fuel mixture. This action is continued until the crankshaft starts rotating the engine by itself.

17.15 Ignition System

An engine's ignition system ignites compressed air-fuel mixture in the cylinder at appropriate times. The ignition system supplies high voltage surges (as much as 20000 volts) of current to produce spark at the spark plug gap. The spark is provided at the exact time in the various cylinders according to the firing order of the engine.

17.16 Charging System

The charging system generates electricity required for the operation of the engine and for the operation of various electrical systems. The main component of the charging system is the alternator, (generator) which produces electricity when driven by the crankshaft via the alternator belt. The alternator produces alternating current, which is converted into direct current through rectifiers installed in the alternator.

When the vehicle is moving, the alternator is driven fast enough to be capable of supplying electricity to various electrical systems and for charging the battery. When the engine is shut down or is running at idling speed, the alternator's output is not sufficient for charging the battery and for high-load electrical devices. The additionally required electricity is supplied by the battery.

17.17 Battery

The battery in an automobile is used as a chemical storage unit for the electrical energy produced

by the alternator. The battery must be capable of delivering high current for the short duration for starting, and it must be able to furnish some or all of the electrical energy for other important system components for short period with the engine idle or off. Typically, system voltages are 12 V for passenger cars and 24 V for commercial vehicles (achieved by connecting two 12V batteries in series). The battery consists of following components:

1. *Casing*. The battery cases are generally made of synthetic resin. Recently, the most common material used is polypropylene. The casing is composed of a lid heat sealed to the molded bottom and sides.

2. *Filler Caps*. The battery filler caps are also made up of synthetic resin. A small hole is made in the cap to permit the escape of oxygen and hydrogen gases while containing the sulphuric acid in the electrolyte.

3. *Battery terminals*. The two terminals of the battery are made of lead alloy. The post-shaped terminals are slightly tapered to have easy connections of the battery leads.

4. *Plates*. A twelve volt (12 V) battery is divided into six cells, each with several sets of positive and negative plates. Each plate is composed of a lead-antimony or lead-calcium alloy grid.

The lead peroxide on the positive plate is a collection of highly porous small brown particles. The lead peroxide breaks down into smaller particles over time and these are dislodged from the grid. The originally porous negative plate gradually loses porosity, contracts and becomes hard. In order to maintain the battery performance and porosity of the negative plate as long as possible, an expanding agent is added to the battery.

The separators are provided between the positive and negative plates in each cell to prevent short circuits between the cells. The separators must be nonconductive and porous while having sufficient mechanical strength and acid resistance. In addition to the separator, glass mats are formed on both sides of the positive plate to prevent loss of the active material and oxidation of lead peroxide.

5. *Electrolyte*. Each cell of the battery is filled with electrolyte or battery solution made up of two parts of pure sulphuric acid* and approximately four parts of distilled water. The contact of the electrolyte with the battery plates generates and stores electricity while improving electrical conductivity. The electrolyte of a fully charged battery contains about 31% sulphuric acid by weight or about 21% by volume in distilled water. This corresponds to specific gravity of 1.23 at 27°C. If impure sulphuric acid is added to the battery, the plates, separators, etc. will becomes corroded, resulting in an increase in self-discharging and shortened battery life. It is, therefore, vital that only pure sulphuric acid and distilled water or water purified by ion exchange be used.

17.18 Working of Battery

The working of battery is based on the principle that an electric current is generated when two kinds of metal having different ionization potential are connected with a conductive wire and submerged in an electrolyte. The electrical energy is converted into potential chemical energy during charging and during discharging, this potential energy is reconverted into electrical energy.

Discharge of battery. When the battery discharges, the positive plates containing lead peroxide (PbO_2) and negative plate having spongy lead (Pb) combine with sulphuric acid (H_2SO_4) to form lead sulphate ($PbSO_4$) and water (H_2O). As discharging continues and the sulphuric acid continues to decompose, the concentration of sulphuric acid in the electrolyte gradually declines.

The amount of sulphuric acid used in the process is proportional to the amount of electricity

* Sulphuric acid (chemical formula H_2SO_4) is a highly corrosive and poisonous acid. Sulphuric acid is soluble in water and reacts with most metals. The melting point is 10° C. This acid is widely used in chemicals, fertilizers, explosives, oil refining etc. Since it has a dehydrating property, therefore, paper and other fibres become carbonised and black when they come in contact with the acid.

drawn from the battery. This means that the specific gravity of the electrolyte reduces in proportion to the consumption of the battery electricity. The amount of electricity remaining in a battery can, therefore, be determined by measuring the specific gravity of the electrolyte.

If discharging continues beyond the limit, the lead sulphate ($PbSO_4$) formed on plates forms into white crystals. This is called *sulphation*. At this point, the chemical reaction is irreversible and the battery cannot be recharged. For all intents and purposes, the battery is "dead".

Charging of battery. When a current from a DC power source (alternator) is applied to a discharged battery, the lead sulphate on the plates is electrochemically decomposed. In this process, sulphur ions are emitted by the plates and the specific gravity of the electrolyte is increased. At the same time, active material on plates return to their original state, *i.e.* to lead peroxide and to spongy lead restoring the battery to full function.

During the final stage of battery charging, the emission of sulphur ions from the plates ceases and at the same time, electrolysis of water in the battery begins. The hydrogen gas is emitted around the negative plate and oxygen gas is emitted around the positive plate.

As a battery is fully charged, the voltage rises gradually. When the battery begins to give off gases, the voltage rises rapidly to the maximum stabilized level. When fully charged, each cell has 2.1 to 2.2 volts. The specific gravity of the elctrolyte also increases gradually during charging until gases are given off because there is a little agitation of the fluid. When the gas emission begins, the specific gravity increases rapidly, reaching the maximum level at the end of charging and remaining constant thereafter.

17.19 Steering System

The purpose of steering system is to change the direction of motion of a vehicle (with the exception of putting the vehicle into reverse). This is done by the rotation of steering wheel by the driver, which changes the orientation of the front wheels.

When the driver operates the steering wheel, the motion is transferred to the steering gearbox via the steering shaft passing through the steering column. It is then converted into lateral motion by this gearbox and transferred to tie-rods. The left and right tie-rods are connected to the steering knuckles on the left and right wheels respectively. Each knuckle is pivoted on the suspension's upper and lower arms and rotate about this axis when force is applied to the knuckle arm. This causes the wheels to move left or right allowing the direction of the vehicle is to be changed.

Note: The ball joints known as rack ends are fitted on the rack and are connected to the tie-rods. These ball-joint connections are provided to compensate for the vertical and axial movements that are caused by suspension movement and steering action.

17.20 Suspension

The suspension is located between the wheels of the vehicle and the body. The suspension system includes springs, shock absorbers and their mountings. The purpose of a suspension system is to improve driving comfort, reduce the amount of vibration and impact forces that are transmitted to the body. It also ensures that the wheels are always firmly in contact with the road surface and regulates the inclination of the body in order to improve the stability of the vehicle in any possible driving condition including acceleration, braking, and cornering.

The suspension system can be divided into two major types based on the design *i.e.* rigid axle and independent type suspension systems.

In the *rigid axle* suspension system, the left and right wheels are connected with a single axle and the load directed to the wheels is supported by this system. The rigid axle suspension is more effective when it is desired to maintain a large suspension stroke in vehicles which exhibit large

variation in load as a result of changes in cargo wieght or passenger numbers. Thus, it is mainly employed in large or medium sized trucks and buses. The drawback of this type of suspension system is that driving comfort and stability are inferior to that of independent type.

In the *independent* type of suspension, there is no axle connecting the left and right wheels, hence the load directed to the wheels is supported by the suspension arms. Thus, each wheel can move independently in response to its specific road condition. Though this type of suspension system is more complicated in terms of design than the rigid axle type, yet the unsprung mass is lighter and wheel-to-ground contact is better. Accordingly, driving comfort and stability are superior when this type of suspension is adopted.

The sprung mass refers to the weight, which is supported by the suspension spring, and the unsprung mass refers to weight, which is not supported by the suspension spring. The unsprung mass includes the weight of wheels, rear axle, steering linkages, and some suspension components. A low unsprung mass has a large effect in improving driving stability.

The independent suspension system has become almost universal in case of front wheels. The following types of independent suspension are generally used in automobiles:

1. *Double wishbone*. A double-wishbone suspension system is comprised of an upper arm, lower arm, and a damper assembly (coil spring and shock absorber) among other components. Each arm is connected to the knuckle and body via bushes. The double wishbone suspension is capable of reducing damper friction and offers a large degree of freedom in design. It is very effective in providing excellent travel and riding comfort.

2. *MacPherson strut*. The MacPherson strut suspension system is comprised of a lower arm and damper assembly. The strut referred contains the damper and a coil spring. The ends of the lower arm are connected to the body and the knuckle via bushes. The upper end of the damper assembly is mounted to the body in such a way that it is allowed to move relative to the body. The lower end is secured to the knuckle.

This design is effective for space saving. The spring is offset in relation to the strut to compensate for bending force imposed when the wheel is driven upwards and downwards. It allows more positive damper action resulting in less noises and smoother ride under all driving conditions.

17.21 Tyres

The tyres basically perform the following functions:

1. It supports the vehicle weight,
2. It transfers the traction and braking force,
3. It changes and maintain the direction of travel, and
4. It absorbs road shocks (due to road irregularities) by acting as a spring in the total suspension system.

A tyre may have a cross ply construction or a radial ply construction as shown in Fig. 17.4 (*a*) and (*b*) respectively. In the *cross ply tyre* construction, the alternate layers of cords run in opposite diagonal directions. It is also known as cross-bias tyre construction. In *radial ply tyre* construction, the cords run radially from bead to bead.

The basic structure of tyre consists of the following components:

1. *Tread*. It is the part which comes into contact with the road surface. The tread is made from a mixture of many different kinds of natural and synthetic rubbers. It protects the body and provides high grip, longer life, maneuverability and durability to the tyre.

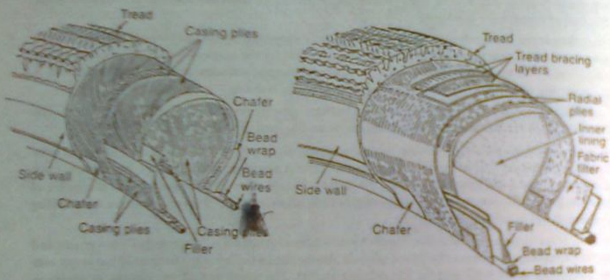
2. *Steel belts*. In steel belted radial tyres, belts made from steel are used to reinforce the area under the tread. These belts provide puncture resistance and help the tyre stay flat so that it makes the best contact with the road.

3. *Bead wires*. The bead is a loop of high strength steel cable coated with rubber. It gives the tyre

the strength it needs to stay seated on the wheel rim and to handle the forces applied by the tyre mounting machines when tyres are installed on rims.

4. *Body.* It sustains the inflation pressure and endures load and road shocks. The body is made up of several layers of different fabrics, called plies. The most commonly used ply fabric is polyester cord.

5. *Sidewall.* It is the most flexible part of the tyre and provides the lateral stability to the tyre.



(*a*) Cross ply tyre construction. (*b*) Radial ply tyre construction.

Fig. 17.4

17.22 Advantages of Radial Tyres over Cross-bias Tyres

The following are the advantages of radial tyres over cross-bias tyres :

1. *Better safety (shorter braking distance).* The braking efficiency of radial tyres on wet roads is better due to stiffer tread and greater side wall flexibility.
2. *Better control.* On turning, a radial tyre has less tendency to distort and lift off the road from one side. Thus, there is a better contact of tyre and hence great stability and precise steering are obtained.
3. *Fewer punctures.* The radial tyres are provided with dual steel belts due to which there is less tendency of puncture in radial tyres.
4. *Lower fuel consumption.* The rolling resistance of radial tyres is lower due to side wall rigidity and stiffer tread due to which fuel consumption is lower.
5. *Greater resistance to wear (longer tread life).* The life of the tyre is normally increased by 50%. This is due to less slip and less internal losses.

Note: The advantage of bias ply tyre over radial ply tyre is smoother ride at low speeds of the vehicle.

17.23 Tyre Size Designation

The tyres are generally specified and designated by the nominal size of their sectional width and the wheel rim diameter.

The *cross-bias ply* tyres are generally designated as: *7.5 × 14 × 6PR*

This designation means that

1. The section width or thickness of tyre from shoulder to shoulder is 7.5 inches.
2. The diameter of the wheel rim is 14 inches.
3. **PR** means ply rating. This represents the maximum recommended load which the tyre can carry when used in a specific condition. It is an index of tyre strength and does not represent necessarily the number of cord plies in the tyre.

The *radial tyres* are generally designated as *145/70 R 12 69 S*

This designation means that

1. The section width or thickness of tyre from shoulder to shoulder is **145 mm**.
2. The aspect ratio is **70%**. The *aspect ratio* is defined as the ratio of section height to section width of the tyre. In this case, it means, the section height is 70% of section width *i.e.* 101.5 mm.
3. **R** represents that the tyre is **radial**.
4. The diameter of the wheel rim is **12 inches**.
5. The load index is **69**. The *load index* defines the maximum load (mass in kg) a tyre can carry under specified condition.
6. The speed symbol is **S**. The *speed symbol* defines the maximum speed for which the tyre is rated to carry a load corresponding to the load index, under specified conditions.

17.24 Wheel Alignment

The wheel alignment relates to the relative position of the wheels with respect to the wheel attaching parts, and the ground. The proper wheel alignment reduces steering effort, provides directional stability and control, reduces tyre side slip and wear. The important alignment factors are as follows:

1. *Camber.* It is the inward or outward tilt of a wheel from the vertical when viewed from the front of the vehicle, as shown in Fig. 17.5(*a*). A wheel that tilts outward from the top has a *positive* camber and if it tilts inwards, then it has a *negative* camber. The camber is measured in degrees and can be adjusted on many vehicles. Generally, positive camber is provided on vehicles to compensate for the wheels tilting inwards due to the weight of the vehicle. The positive camber also places the centreline of the wheel closer to the steering axis. The distance between the wheel centreline and the steering axis centreline at the point where they intersect the road surface is called *camber offset*. The smaller

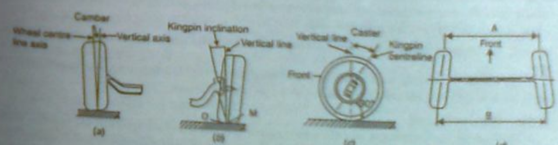


Fig. 17.5

the offset, the smaller is the effort required to steer the vehicle. But, excessive camber will, however cause uneven tyre wear and loss of traction.

(*b*) *Kingpin inclination (Steering axis inclination).* The kingpin (ball joint centreline) inclination is the inward tilt of the kingpin from the vertical as viewed from the front of the vehicle, as shown in Fig. 17.5 (*b*). Sometimes, an extended line drawn through the king pin inclination intersects the ground at a point O different from the centre of the tyre's ground contact M. The difference in these two points is called the *scrub radius*.

This helps in return of the wheels to the straight-ahead position after a turn has been made. This also helps to reduce camber offset in a way that it brings the wheel centreline and the steering axis centreline closer together where they intersect the road surface, which has the corresponding effect of reducing the effort required to steer the vehicle.

(*c*) *Caster*. It is the tilt of the kingpin towards the front or the rear of the vehicle, as shown in Fig. 17.5 (*c*). If the tilt is towards the rear, the wheel has a positive caster and if it tilts towards front, then it has a negative caster.

This positive caster generates a steering-aligning torque. It tends to force the wheels to travel in a straight ahead position, and it also assists in return of the wheel to the straight ahead position after a turn has been made, thus maintaining directional stability.

(*d*) Toe-in. The front of the wheels is drawn inwards such as that the distance between the front ends is slightly less than the distance between the back ends. In Fig. 17.5 (*d*), the distance 'A' is less than the distance '*B*'. The difference in these distances is called toe-in and is measured in millimetres. In the reverse case, when the front of the wheels are angled outwards, the condition is called *toe-out*.

The purpose of toe-in is to ensure parallel rolling of wheels, to stabilize steering, and to prevent both side-slipping and excessive wear of the tyres.

17.25 Wheel Balance

The weight of the wheel (wheel rim & tyre assembly) should be distributed evenly to create the balanced condition. If the weight is distributed unevenly, centrifugal forces cause the wheel to vibrate as it turns. A slight imbalance causes vibrations on the steering wheel. More serious imbalance causes complete body vibrations. There are two types of wheel balance:

1. *Static wheel balance*. The static balance is the equal distribution of weight around the wheel. A statically balanced wheel does not rotate by itself regardless of the position in which it is placed on its axis. On the other hand, a statically imbalanced (off axis) wheel tends to rotate by itself until the heaviest portion reaches the bottom. During vehicle operation, static imbalance causes a bouncing action that leads to uneven tyre wear.

2. *Dynamic wheel balance*. The dynamic balance is the equal distribution of weight on each side of the wheel's centreline (as seen from the front or rear). During vehicle operation, a dynamically imbalanced (off-centre) wheel experience side-to-side deflection, leading to vibration in the steering wheel or body and to bald spots on the tyre.

Notes: 1. In order to correct static imbalance, a weight is attached to the wheel directly opposite to the heaviest spot.

2. In order to correct dynamic imbalance, equal weights are placed 180 degrees apart from each other, one on the inside of the wheel and one on the outside, at the point of imbalance.

17.26 Braking System

The braking system reduces wheel rotating speed in order to reduce speed of the vehicle. When brakes are applied on a moving vehicle, the kinetic energy of motion of the vehicle is transformed into heat generated by the friction between the brake lining and the rotating drum (or disc). The heat generated is dissipated into the surrounding air. The braking systems which are commonly used in all automobiles is shown in Fig. 17.6, and is discussed below:

1. *Parking brake*. It is used to hold the vehicle stationary, when applied. At the time of parking, the braking is necessary to prevent the vehicle from rolling off due to road gradient or blowing wind. The brake manually operates on the rear wheels through cables or mechanical linkage from an auxiliary foot lever (or a hand pull). It is held on by a ratchet until released by some means such as a push button or a lever.

2. *Service brake (Main system)*. The most automotive service brakes are hydraulic brakes. The hydraulic action begins when force is applied to the brake pedal. This force creates pressure in the

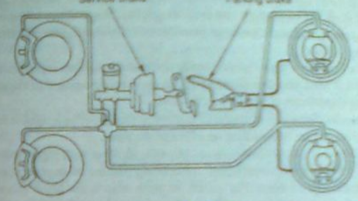


Fig. 17.6

master cylinder, either directly or through a power booster. It serves to displace hydraulic fluid stored in master cylinder. The displaced fluid transmits the pressure through the fluid filled brake lines to the wheel cylinders that actuate the brake shoe (or pad mechanism). The actuation of these mechanisms forces the brake pads and linings against the rotors (front wheels) or drums (rear wheels) to stop the wheels.

The master cylinder of a brake system converts pedal force into hydraulic pressure to operate the brakes. When the brake pedal is depressed, pistons in the master cylinder are activated, causing pressure to act on the brake fluid. When the brake pedal is released, return springs move the pistons back to their original positions.

Generally, all the vehicles utilise tandem master cylinders. This type of master cylinder serves two independent hydraulic lines. Since both hydraulic lines are independent, therefore, the fluid loss or other abnormalities in one line do not cause all the brakes to fail.

The master cylinder is fitted with a brake fluid reservoir. The fluid in the reservoir compensates for variations in the fluid level that accompany movement of pistons and for permanent changes in the quantity of fluid in the brake lines that occur as the brake pads become worn.

Note: When the brake pads are worn, the caliper piston must have longer stroke so that pads make a contact with the disc. Thus, more fluid is required in the brake line.

17.27 Disc and Drum Brake

Mostly all cars have disc brake on the front wheels, and some have disc brakes on all the four wheels. A *disc brake* uses a flat, round disc (or rotor), attached to the wheel hub instead of drum. The brake shoes, also called pads, are positioned on opposite sides of the rotor and are mounted in the brake caliper. The caliper contains the hydraulic pistons used to apply the shoes and to the suspension members. Most brake discs are solid, but some vehicle have ventilated discs which contains radial vanes between its rubbing surfaces for optimum cooling performance.

The *drum brake* is the traditional type of brake and is currently used in rear wheels of many vehicles. The pan shaped drum is attached to the axle or hub flange, just inside the wheel, and it rotates directly with the wheel. The brake shoes are positioned just inside the drum and are mounted on the backing plate. The shoes are anchored to the backing plate so that they can pivot in and out of contact with the drum but cannot rotate with it. The anchors can be arranged in such a way that an opening of the shoe is placed over a round anchor or the smooth end of the shoe butts against a flat anchor block. The braking forces are transmitted from the shoe to the anchors, to the backing plate, and then to the suspension members.

17.28 Painting of Automobiles

An automobile is mostly made from steel sheets. When it is exposed to air, the steel tends to produce rust on it. Once rust starts to grow over the steel objects, it becomes difficult to keep the characteristics of steel like its strength and even its original shape. Thus by painting over it, rust is prevented from growing on it and it becomes possible to retain its original charateristics much longer than without being painted.

The paint is a liquid of a high viscosity made up from the various ingredients evenly mixed up. Normally, the paint is used after it is diluted with an appropriate amount of thinner so that it can be easily applied. The ingredients of paint are as follows:

1. *Pigments.* The pigment is a powder of extremely tiny particles insolubie in water, oil and any other solvent. It gives colour and a filling up effect to the paint.
2. *Resins.* The resin is a main constituent of paint, together with pigment it forms a paint layer which is normally a sticky transparent liquid. After being painted on an object (automobile) and dry hardened, it becomes a paint layer. The quality of resin affects the finish (luster, brightness), the easiness of work (drying, polishing) and the quality of paint layer (hardness, anti-solution, weather proofing).
3. *Solvent.* It is a liquid for melting resin to make pigments and resin mix easily. Since various kinds of resins are used in paint, therefore, to dissolve them all, different kinds of solvents must be used.
4. *Thinner.* The thinner is a mixture of several solvents and is added in paints to optimise its viscosity so that paint can be applied easily. It is made up of several different soluble liquids. The solvents and thinner evaporates as the paint dries and does not remain in the paint layer.
5. *Additives.* These are added to improve the characteristics and quality of paint and paint layers.
6. *Hardener.* It is used to make paint film hard. Acrylic urethane paint is mainly used for car paint repair along with isocyanine chemical as hardener.

OBJECTIVE TYPE QUESTIONS

1. Which of the following is not an automobile ?
   (a) Motor cycle (b) Passenger car
   (c) Aeroplane (d) Truck
2. In a unit type body (frameless body) design, the sheet metal parts are welded together, forming a frame work to which outer skin is attached.
   (a) True (b) False
3. In comparison to frame type construction, the frameless structure construction of automobiles is economical when produced in .... numbers.
   (a) small (b) large
4. The torque available at the contact between driving wheels and road is known as
   (a) brake effort (b) tractive effort
   (c) clutch effort (d) none of these
5. The engine torque increases with the increase in engine speed up to a certain point after which it starts to fall down.
   (a) Correct (b) Incorrect
6. The rolling resistance is because of the friction between the
   (a) wheel rim and tyre (b) tyre and the road surface
   (c) wheel rim and road surface (d) none of these

7. The co-efficient of rolling resistance for a truck weighing 63 500 N is 0.018. The rolling resistance to the truck is
   (a) 1.143 N (b) 11.43 N (c) 114.3 N (d) 1143 N
8. A petrol engine of a car develops 125 N-m torque at 2700 r.p.m. The car is driven in second gear having gear ratio of 1.75. The final drive ratio is 4.11. If the overall transmission efficiency is 90%, then the torque available at the driving wheels is
   (a) 8.091 N-m (b) 80.91 N-m (c) 809.1 N-m (d) 8091 N-m
9. The air resistance to a car at 20 kmph is R. The air resistance at 40 kmph will be
   (a) R (b) $2R$ (c) $4R$ (d) $4R^2$
10. The gradient resistance to a vehicle having a mass of 980 kg moving on an incline of 10° is
    (a) 1.6694 N (b) 16.694 N (c) 166.94 N (d) 1669.4 N
11. The power actually developed inside the engine cylinder is called as
    (a) indicated power (b) brake power (c) frictional power (d) none of these
12. The most commonly used power plant in automobiles is
    (a) gas turbine (b) I.C. engine (c) battery (d) none of these
13. The petrol engine works on
    (a) Otto cycle (b) Carnot cycle (c) Diesel cycle (d) Rankine cycle
14. In a square type engine
    (a) geometrical shape is square
    (b) diameter and length of piston are same
    (c) two cylinders are placed horizontal and two vertical
    (d) stroke length and cylinder bore are same
15. The three basic cylinder arrangements for automotive engines are
    (a) flat, radial, and V (b) in a row, in line, and opposed
    (c) in line, V, and opposed (d) V, double row, and opposed
16. The petrol engines are also known as
    (a) spark ignition (S.I.) engines (b) compression ignition (C.I.) engines
    (c) steam engines (d) none of these
17. The Diesel engine works on
    (a) Otto cycle (b) Carnot cycle
    (c) Diesel cycle (d) Rankine cycle
18. The Diesel engines are also known as
    (a) spark ignition (S.I.) engines (b) compression ignition (C.I.) engines
    (c) steam engines (d) none of these
19. For the same maximum pressure and temperature
    (a) Diesel cycle is more efficient than Otto cycle
    (b) Otto cycle is more efficient than Diesel cycle
    (c) both Otto cycle and Diesel cycle are equally efficient
    (d) none of the above