AN INTRODUCTION TO

THERMODYNAMICS

THIS IS AN INTRODUCTION CHAPTER TO THERMODYNAMICS. THIS IS A CHAPTER TAKEN FROM FIRST CHAPTER OF IC ENGINE BY RK RAJPUT.

For More Visit:www.LearnEngineering.in

1

Basic Concepts of Thermodynamics

1.1. Definition of thermodynamics. 1.2. Thermodynamic systems—System, boundary and surroundings—Closed system—Open system—Isolated system—Adiabatic system—Homogeneous system—Heterogeneous system. 1.3. Pure substance. 1.4. Thermodynamic equilibrium. 1.5. Properties of systems. 1.6. State. 1.7. Process. 1.8. Cycle. 1.9. Point function. 1.10. Path function. 1.11. Temperature. 1.12. Zeroth law of thermodynamics. 1.13. Pressure—Definition of pressure—Unit for pressure—Types of pressure measurement devices. 1.14. Reversible and irreversible processes. 1.15. Energy, work and heat—Energy—Work and heat. 1.16. First law of thermodynamics. 1.17. The perfect gas—The characteristic equation of state—Specific heats—Joule's law—Relationship between two specific heats—Enthalpy—Ratio of specific heats. 1.18. Steady flow energy equation (S.F.E.E.)—Energy relations for flow process. 1.19. Limitations of first law of thermodynamics. 1.20. Performance of heat engine and reversed heat engine. 1.21. Statements of second law of thermodynamics—Clausius statement Kelvin-Planck statement. 1.22. Entropy—Introduction—Temperature entropy diagram—Characteristics of entropy. 1.23. The third law of thermodynamics. 1.24. Available and unavailable energy—Highlights—Objective Type Questions—Theoretical Questions.

1.1. DEFINITION OF THERMODYNAMICS

Thermodynamics may be defined as follows :

Thermodynamics is an axiomatic science which deals with the relations among heat, work and properties of system which are in equilibrium. It describes state and changes in state of physical systems.

Or

Thermodynamics is *the science of the regularities governing processes of energy conversion.*

Or

Thermodynamics is *the science that deals with the interaction between energy and material systems.*

Thermodynamics, basically entails *four laws* or axioms known as Zeroth, First, Second and Third law of thermodynamics.

— the *First law* throws light on *concept of internal energy*.

— the *Zeroth law* deals with *thermal equilibrium* and establishes a *concept of temperature*.

— the *Second law* indicates the limit of *converting heat into work* and introduces the *principle of increase of entropy*.

— third law defines the *absolute zero of entropy*.

These laws are based on experimental observations and have no *mathematical proof*. Like all physical laws, these laws are based on *logical reasoning*.

Copyrighted material

For More Visit:www.LearnEngineering.in

1.2. THERMODYNAMIC SYSTEMS

1.2.1. System, Boundary and Surroundings

System. A system is *a finite quantity of matter or a prescribed region of space* (Refer Fig. 1.1)

Boundary. The *actual or hypothetical envelope enclosing the system* is the boundary of the system. The boundary may be fixed or it may move, as and when a system containing a gas is compressed or expanded. The boundary may be *real* or *imaginary*. It is not difficult to envisage a real boundary but an example of imaginary boundary would be one drawn around a system consisting of the fresh mixture about to enter the cylinder of an I.C. engine together with the remanants of the last cylinder charge after the exhaust process (Refer Fig. 1.2).

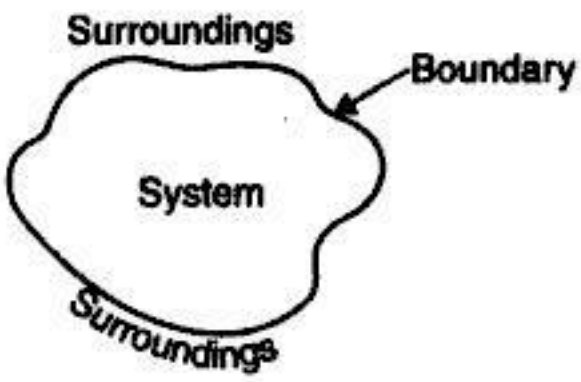


Fig. 1.1. The system.

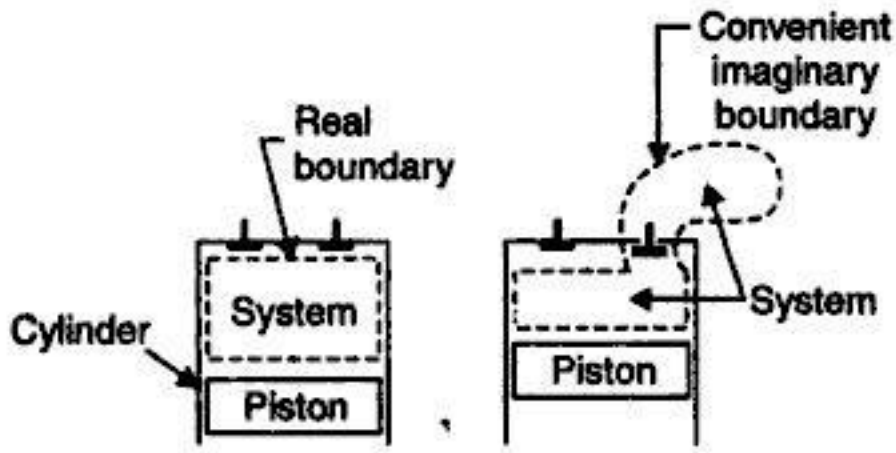


Fig. 1.2. The real and imaginary boundaries.

1.2.2. Closed System

Refer Fig. 1.3. If the boundary of the system is impervious to the flow of matter, it is called a *closed system*. An example of this system is mass of gas or vapour contained in an engine cylinder, the boundary of which is drawn by the cylinder walls, the cylinder head and piston crown. Here the *boundary is continuous and no matter may enter or leave.*

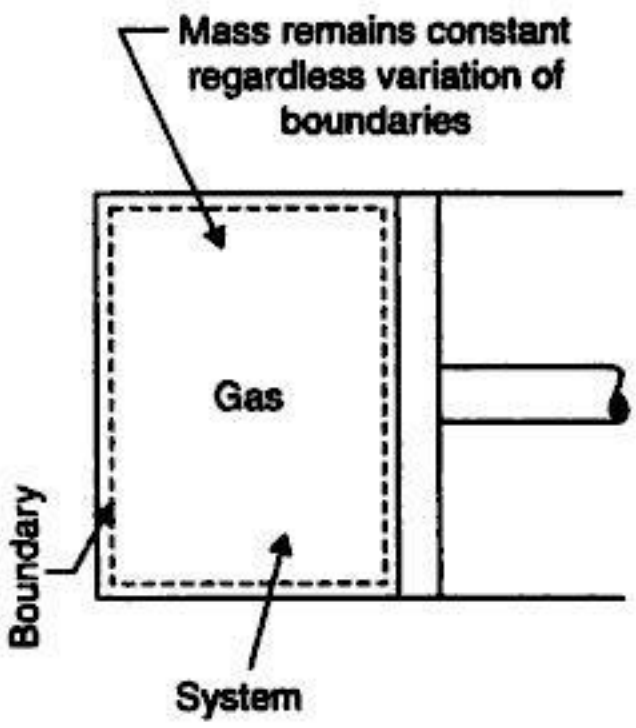


Fig. 1.3. Closed system.

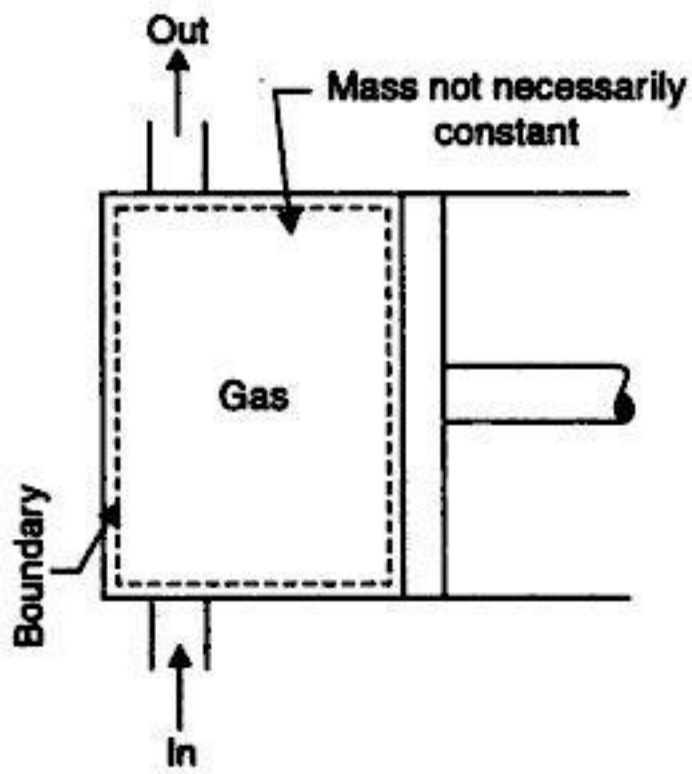


Fig. 1.4. Open system.

1.2.3. Open System

Refer Fig. 1.4. An open system is one in which *matter flows into or out of the system*. Most of the engineering systems are open.

Copyrighted material

For More Visit:www.LearnEngineering.in

For More Visit:www.LearnEngineering.in

1.2.4. Isolated System

An isolated system is that system *which exchanges neither energy nor matter with any other system or with environment.*

1.2.5. Adiabatic System

An adiabatic system is one *which is thermally insulated from its surroundings*. It can, however, *exchange work with its surroundings*. If it does not, it becomes an isolated system.

Phase. A phase is a quantity of matter which is homogeneous throughout in chemical composition and physical structure.

1.2.6. Homogeneous System

A system which consists of a single phase is termed as *homogeneous system*. Examples : Mixture of air and water vapour, water plus nitric acid and octane plus heptane.

1.2.7. Heterogeneous System

A system which consists of two or more phases is called a *heterogeneous system*. Examples : Water plus steam, ice plus water and water plus oil.

1.3. PURE SUBSTANCE

A pure substance is one that has a homogeneous and invariable chemical composition even though there is a change of phase. In other words, it is a system which is (*a*) homogeneous in composition, (*b*) homogeneous in chemical aggregation. Examples : Liquid, water, mixture of liquid water and steam, mixture of ice and water. The mixture of liquid air and gaseous air is not a pure substance.

1.4. THERMODYNAMIC EQUILIBRIUM

A system is in *thermodynamic equilibrium* if the temperature and pressure at all points are same ; there should be no velocity gradient ; the chemical equilibrium is also necessary. Systems under temperature and pressure equilibrium but not under chemical equilibrium are sometimes said to be in metastable equilibrium conditions. *It is only under thermodynamic equilibrium conditions that the properties of a system can be fixed.*

Thus for attaining a state of *thermodynamic equilibrium* the following three types of equilibrium states must be achieved :

1. **Thermal equilibrium.** The temperature of the system does not change with time and has same value at all points of the system.

2. **Mechanical equilibrium.** There are no unbalanced forces within the system or between the surroundings. The pressure in the system is same at all points and does not change with respect to time.

3. **Chemical equilibrium.** No chemical reaction takes place in the system and the chemical composition which is same throughout the system does not vary with time.

1.5. PROPERTIES OF SYSTEMS

A property of a system is a characteristic of the system which depends upon its state, but not upon how the state is reached. There are two sorts of property :

1. **Intensive properties.** These properties *do not depend on the mass of the system. Examples* : Temperature and pressure.

Copyrighted material

For More Visit:www.LearnEngineering.in

2. **Extensive properties.** These properties *depend on the mass of the system. Example* : Volume. Extensive properties are often divided by mass associated with them to obtain the intensive properties. For example, if the volume of a system of mass m is V, then the specific volume of matter within the system is $\frac{V}{m} = v$ which is an intensive property.

1.6. STATE

State *is the condition of the system at an instant of time as described or measured by its properties. Or each unique condition of a system is called a state.*

It follows from the definition of state that each property has a single value at each state. Stated differently, all properties are *state* or *point functions.* Therefore, all properties are identical for identical states.

On the basis of the above discussion, we can determine if a given variable is *property* or not by applying the following *tests* :

— *A variable is a property, if and only if, it has a single value at each equilibrium state.*

— *A variable is a property, if and only if, the change in its value between any two prescribed equilibrium states is single-valued.*

Therefore, *any variable whose change is fixed by the end states is a property.*

1.7. PROCESS

A process occurs when the system undergoes a change in a state or an energy transfer at a steady state. A process may be *non-flow* in which a fixed mass within the defined boundary is undergoing a change of state. Example : a substance which is being heated in a closed cylinder undergoes a non-flow process (Fig. 1.3). *Closed systems undergo non-flow processes.* A process may be a flow process in which mass is entering and leaving through the boundary of an open system. In a steady flow process (Fig. 1.4) mass is crossing the boundary from surroundings at entry, and an equal mass is crossing the boundary at the exit so that the total mass of the system remains constant. In an open system it is necessary to take account of the work delivered from the surroundings to the system at entry to cause the mass to enter, and also of the work delivered from the system at surroundings to cause the mass to leave, as well as any heat or work crossing the boundary of the system.

Quasi-static process. Quasi means 'almost'. A quasi-static process is also called a *reversible process. This process is a succession of equilibrium states and infinite slowness is its characteristic feature.*

1.8. CYCLE

Any process or series of processes whose end states are identical is termed a ***cycle.*** The processes through which the system has passed can be shown on a state diagram, but a complete section of the path requires in addition a statement of the heat and work crossing the boundary of the system. Fig. 1.5 shows such a cycle in which a system commencing at condition '1' changes in pressure and volume through a path 123 and returns to its initial condition '1'.

Copyrighted material

For More Visit:www.LearnEngineering.in

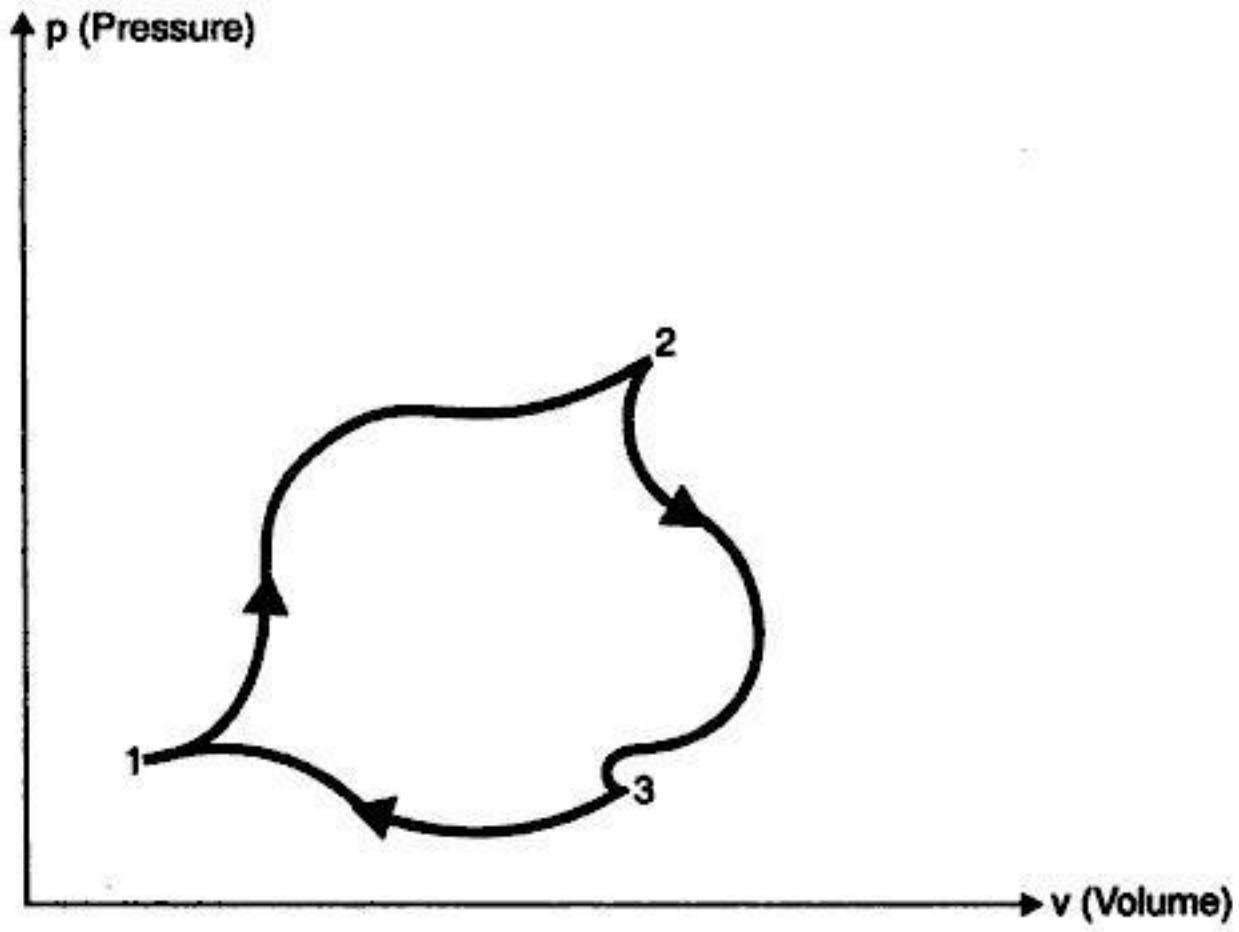


Fig. 1.5. Cycle of operations.

1.9. POINT FUNCTION

When two properties locate a *point* on the graph (co-ordinate axes) then those properties are called as *point function*.

Examples. Pressure, temperature, volume etc.

$$\int_1^2 dV = V_2 - V_1 \text{ (an } \textit{exact differential}\text{).}$$

1.10. PATH FUNCTION

There are certain quantities which cannot be located on a graph by a *point* but are given by the *area* or so, on that graph. In that case, the area on the graph, pertaining to the particular process, is a function of the path of the process. Such quantities are called *path functions*.

Examples. Heat, work etc.

Heat and work are *inexact differentials*. Their change cannot be written as difference between their end states.

Thus $\int_1^2 \delta Q \neq Q_2 - Q_1$ and is shown as ${}_1Q_2$ or Q_{1-2}

Similarly $\int_1^2 \delta W \neq W_2 - W_1$, and is shown as ${}_1W_2$ or W_{1-2}

Note. The operator δ is used to denote inexact differentials and operator d is used to denote exact differentials.

1.11. TEMPERATURE

- *The temperature is a thermal state of a body which distinguishes a hot body from a cold body*. The temperature of a body is *proportional to the stored molecular energy i.e.* the average molecular kinetic energy of the molecules in a system. (A particular molecule does not have a temperature, it has energy. The gas as a system has temperature).

Copyrighted material

For More Visit:www.LearnEngineering.in

- Instruments for measuring ordinary temperatures are known as "*thermometers*" and those for measuring high temperatures are known as "*pyrometers*".
- It has been found that a gas will not occupy any volume at a certain temperature. This temperature is known as *absolute zero temperature*. The temperatures measured with absolute zero as basis are called *absolute temperatures*. Absolute temperature is stated in degrees centigrade. The point of absolute temperature is found to occur at 273.15°C below the freezing point of water.

Then : Absolute temperature = Thermometer reading in °C + 273.15.

Absolute temperature in degree centigrade is known as degrees kelvin, denoted by K (SI unit).

1.12. ZEROTH LAW OF THERMODYNAMICS

- **'Zeroth law of thermodynamics'** *states that if two systems are each equal in temperature to a third, they are equal in temperature to each other.*

Example. Refer Fig. 1.6. System '1' may consist of a mass of gas enclosed in a rigid vessel fitted with a pressure gauge. If there is no change of pressure when this system is brought into contact with system '2' a block of iron, then the two systems are equal in temperature (assuming that the systems 1 and 2 do not react each other chemically or electrically). Experiment reveals that if system '1' is brought into contact with a third system '3' again with no change of properties then systems '2' and '3' will show no change in their properties when brought into contact provided they do not react with each other chemically or electrically. Therefore, '2' and '3' must be in equilibrium.

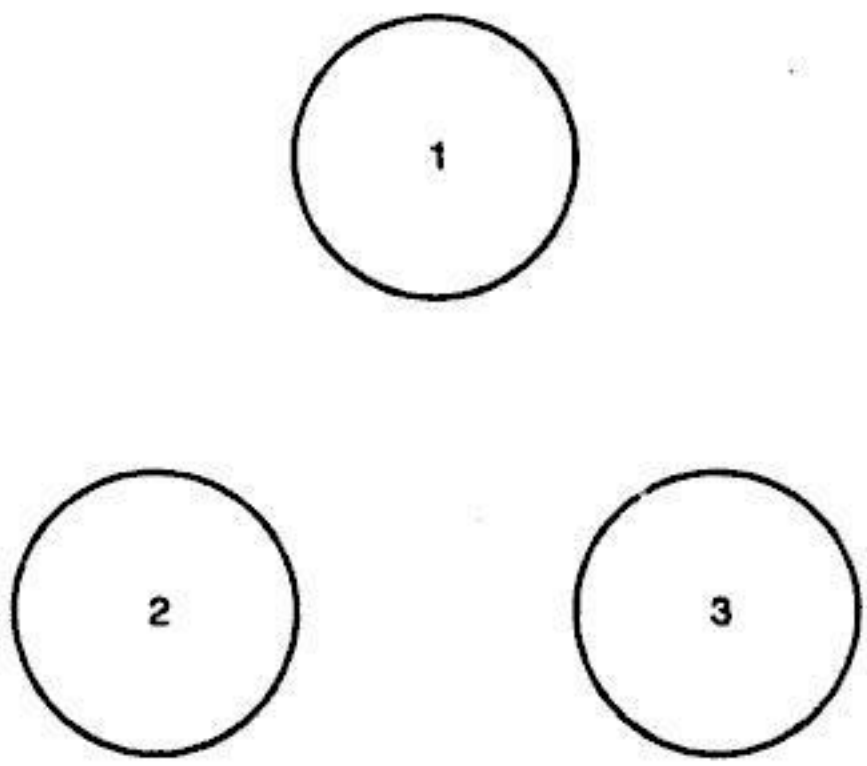


Fig. 1.6. Zeroth law of thermodynamics.

- This law was enunciated by R.H. Fowler in the year 1931. However, since the first and second laws already existed at that time, it was designated as *zeroth law* so that it *precedes* the first and second laws *to form a logical sequence*.

1.13. PRESSURE

1.13.1. Definition of Pressure

Pressure is defined as a *force per unit area*. Pressures are exerted by gases, vapours and liquids. The instruments that we generally use, however, record pressure as the difference

Copyrighted material

For More Visit:www.LearnEngineering.in

between two pressures. Thus, it is the *difference between the pressure exerted by a fluid of interest and the ambient atmospheric pressure.* Such devices indicate the pressure either above or below that of the atmosphere. When it is *above the atmospheric pressure*, it is termed *gauge pressure* and is *positive*. When it is *below* atmospheric, it is *negative* and is known as *vacuum*. Vacuum readings are given in millimetres of mercury or millimetres of water below the atmosphere.

It is necessary to establish an absolute pressure scale which is independent of the changes in atmospheric pressure. A pressure of absolute zero can exist only in complete vacuum. *Any pressure measured above the absolute zero of pressure* is termed an *'absolute pressure'*.

A schematic diagram showing the *gauge pressure, vacuum pressure* and the *absolute pressure* is given in Fig. 1.7.

Mathematically :

(*i*) Absolute pressure = Atmospheric pressure + Gauge pressure

$$p_{abs.} = p_{atm.} + p_{gauge}.$$

(*ii*) Vacuum pressure = Atmospheric pressure – Absolute pressure.

Vacuum is defined as the *absence of pressure*. A *perfect vacuum* is obtained when *absolute pressure is zero*, at this instant *molecular momentum is zero*.

Atmospheric pressure is measured with the help of barometer.

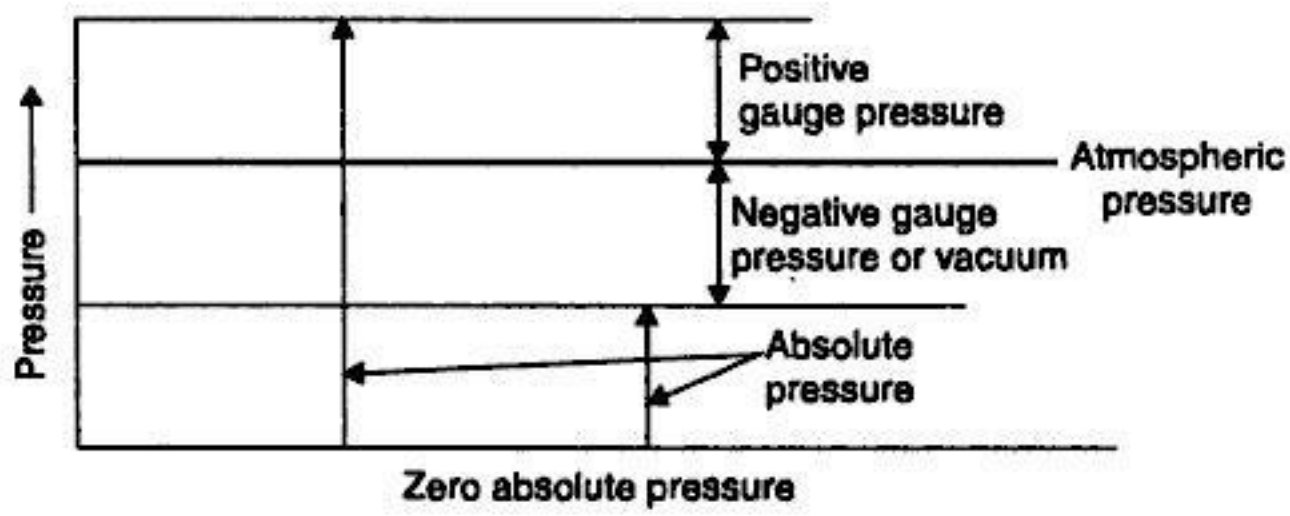


Fig. 1.7. Schematic diagram showing gauge, vacuum and absolute pressures.

1.13.2. Unit for Pressure

The fundamental SI unit of pressure is N/m^2 (sometimes called *pascal*, Pa) or bar. 1 bar = 10^5 N/m^2 = 10^5 Pa. Standard atmospheric pressure = 1.01325 bar = 0.76 m Hg.

Low pressures are often expressed in terms of mm of water or mm of mercury. This is an abbreviated way of saying that the pressure is such that which will support a liquid column of stated height.

1.13.3. Types of Pressure Measurement Devices

The pressure may be measured by means of indicating gauges or recorders. These instruments may be mechanical, electro-mechanical, electrical or electronic in operation.

1. **Mechanical instruments.** These instruments may be classified into following two groups :

— The *first group* includes those instruments in which the *pressure* measurement is made by *balancing an unknown force with a known force.*

— The *second group* includes those employing *quantitative deformation of an elastic member for pressure measurement.*

Copyrighted material

For More Visit:www.LearnEngineering.in

2. **Electro-mechanical instruments.** These instruments usually *employ a mechanical means for detecting the pressure and electrical means for indicating or recording the detected pressure.*

3. **Electronic instruments.** Electronic pressure measuring instruments normally depend on some physical change that can be detected and indicated or recorded electronically.

1.14. REVERSIBLE AND IRREVERSIBLE PROCESSES

Reversible process. *A reversible process (also sometimes known as quasi-static process) is one which can be stopped at any stage and reversed so that the system and surroundings are exactly restored to their initial states.*

This process has the following *characteristics* :

1. It must pass through the same states on the reversed path as were initially visited on the forward path.

2. This process when undone will leave no history of events in the surroundings.

3. It must pass through a continuous series of equilibrium states.

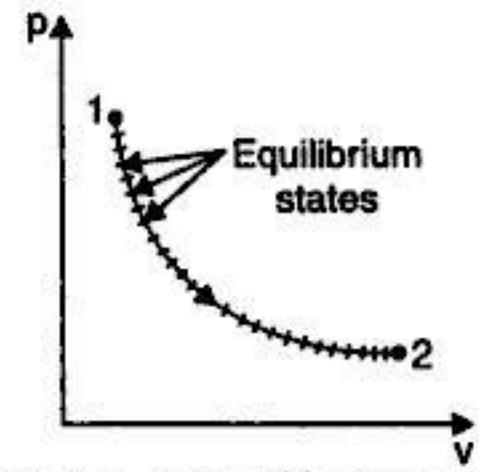


Fig. 1.8. Reversible process.

No real process is truely reversible but some processes may approach reversibility, to close approximation.

Examples. Some *examples of nearly reversible processes* are :

(*i*) Frictionless relative motion.

(*ii*) Expansion and compression of spring.

(*iii*) Frictionless adiabatic expansion or compression of fluid.

(*iv*) Polytropic expansion or compression of fluid.

(*v*) Isothermal expansion or compression.

(*vi*) Electrolysis.

Irreversible process. An *irreversible process is one in which heat is transferred through a finite temperature.*

Examples :

(*i*) Relative motion with friction (*ii*) Combustion

(*iii*) Diffusion (*iv*) Free expansion

(*v*) Throttling (*vi*) Electricity flow through a resistance

(*vii*) Heat transfer (*viii*) Plastic deformation.

An irreversible process is usually represented by a dotted (or discontinuous) line joining the end states to indicate that the intermediate states are indeterminate (Fig. 1.9).

Irreversibilities are of *two types* :

1. **External irreversibilities.** These are associated with *dissipating effects outside the working fluid.*

Example. *Mechanical friction occurring during a process due to some external source.*

2. **Internal irreversibilities.** These are associated with *dissipating effects within the working fluid.*

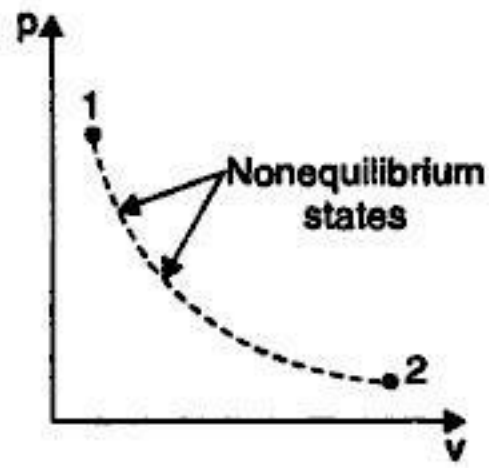


Fig. 1.9. Irreversible process.

Example. *Unrestricted expansion of gas, viscosity and inertia of the gas.*

Copyrighted material

For More Visit:www.LearnEngineering.in

For More Visit:www.LearnEngineering.in

1.15. ENERGY, WORK AND HEAT

1.15.1. Energy

Energy is a general term embracing *energy in transition* and *stored energy*. The stored energy of a substance may be in the forms of *mechanical energy* and *internal energy* (other forms of stored energy may be chemical energy and electrical energy). Part of the stored energy may take the form of either potential energy (which is the gravitational energy due to height above a chosen datum line) or kinetic energy due to velocity. The balance part of the energy is known as *internal energy*. In a *non-flow process* usually there is no change of potential or kinetic energy and hence change of mechanical energy will not enter the calculations. In a *flow process*, however, there may be changes in both potential and kinetic energy and these must be taken into account while considering the changes of stored energy. ***Heat and work*** are *the forms of energy in transition*. These are the only forms in which energy can cross the boundaries of a system. *Neither heat nor work can exist as stored energy.*

1.15.2. Work and Heat

Work

Work is said to be done when a *force moves through a distance*. If a part of the boundary of a system undergoes a displacement under the action of a pressure, the work done W is the product of the force (pressure × area), and the distance it moves in the direction of the force. Fig. 1.10 (*a*) illustrates this with the conventional piston and cylinder arrangement, the heavy line defining the boundary of the system. Fig. 1.10 (*b*) illustrates another way in which work might be applied to a system. A force is exerted by the paddle as it changes the momentum of the fluid, and since this force moves during rotation of the paddle room work is done.

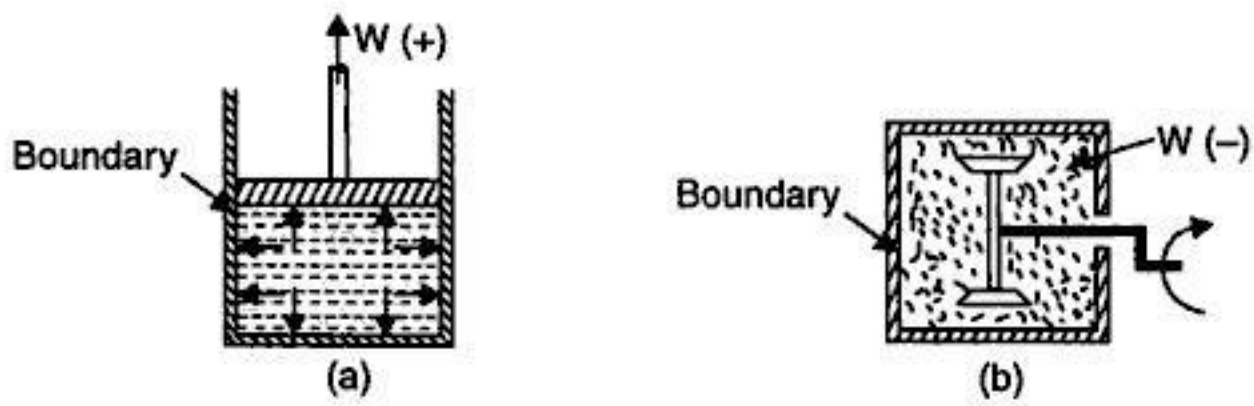


Fig. 1.10

"Work" is a transient quantity which only appears at the boundary while a change of state is taking place within a system. "Work" is 'something' which appears at the boundary when a system changes its state due to the movement of a part of the boundary under the action of a force.

Sign convention :

- If the work is done *by* the system *on* the surroundings, *e.g.* when a fluid expands pushing a piston outwards, the work is said to be *positive*.

i.e., *Work output of the system* = + W

- If the work is done *on* the system *by* the surroundings, *e.g.* when a force is applied to a rotating handle, or to a piston to compress a fluid, the work is said to be *negative*.

i.e., *Work input to system* = – W

Copyrighted material

For More Visit:www.LearnEngineering.in

Heat

Heat (denoted by the symbol Q), may be, defined in an analogous way to work as follows :

"Heat is 'something' which appears at the boundary when a system changes its state due to a difference in temperature between the system and its surroundings".

Heat, like work, is a *transient quantity* which only appears at the boundary while a change is taking place within the system.

It is apparent that neither δW or δQ are exact differentials and therefore any integration of the elemental quantities of work or heat which appear during a change from state 1 to state 2 must be written as

$$\int_1^2 \delta W = W_{1-2} \text{ or } {}_1W_2 \text{ (or } W\text{), and}$$

$$\int_1^2 \delta Q = Q_{1-2} \text{ or } {}_1Q_2 \text{ (or } Q\text{)}$$

Sign convention :

If the heat flows *into* a system *from* the surroundings, the quantity is said to be *positive* and, conversely, if heat flows *from* the system to the surroundings it is said to be *negative*.

In other words :

Heat received by the system = + Q

Heat rejected or given up by the system = – Q.

Comparison of Work and Heat

Similarities :

(*i*) Both are *path functions and inexact differentials.*

(*ii*) Both are boundary phenomenon *i.e.*, both are recognized at the boundaries of the system as they cross them.

(*iii*) Both are associated with a process, not a state. Unlike properties, work or heat has no meaning at a state.

(*iv*) Systems possess energy, but not work or heat.

Dissimilarities :

(*i*) In heat transfer temperature difference is required.

(*ii*) In a stable system there cannot be work transfer, however, there is no restriction for the transfer of heat.

(*iii*) The sole effect external to the system could be reduced to rise of a weight but in the case of a heat transfer other effects are also observed.

1.16. FIRST LAW OF THERMODYNAMICS

It is observed that when a system is made to undergo a complete cycle then net work is done *on* or *by* the system. Consider a cycle in which net work is done by the system. Since energy cannot be created, this mechanical energy must have been supplied from some source of energy. Now the system has been returned to its initial state : Therefore, its *intrinsic* energy is unchanged, and hence the mechanical energy has not been provided by the system itself. The only other energy involved in the cycle is the heat which was supplied and rejected in various processes. Hence, by the law of conservation of energy, the net work done by the system is equal to the net heat supplied

Copyrighted material

For More Visit:www.LearnEngineering.in

For More Visit:www.LearnEngineering.in

to the system. The First Law of Thermodynamics can, therefore, be stated as follows :

"When a system undergoes a thermodynamic cycle then the net heat supplied to the system from the surroundings is equal to net work done by the system on its surroundings.

or
$$\oint dQ = \oint dW$$

where $\oint$ represents the sum for a complete cycle.

The first law of Thermodynamics *cannot be proved analytically, but experimental evidence has repeatedly confirmed its validity*, and since no phenomenon has been shown to contradict it, the first law is accepted as a *law of nature*. It may be remarked that no restriction was imposed which limited the application of first law to reversible energy transformation. Hence the first law applies to reversible as well as irreversible transformations : For non-cyclic process, a more general formulation of first law of thermodynamics is required. A new concept which involves a term called *internal energy* fulfills this need.

— The First Law of Thermodynamics may also be stated as follows :

"Heat and work are mutually convertible but since energy can neither be created nor destroyed, the total energy associated with an energy conversion remains constant".

Or

— **"No machine can produce energy without corresponding expenditure of energy, *i.e.*, it is impossible to construct a perpetual motion machine of first kind".**

1.17. THE PERFECT GAS

1.17.1. The Characteristic Equation of State

— At temperatures that are considerably in excess of critical temperature of a fluid, and also at very low pressure, the vapour of fluid tends to obey the equation

$$\frac{pv}{T} = \text{constant} = R$$

In practice, no gas obeys this law rigidly, but many gases tend towards it.

An imaginary ideal gas which obeys this law is called a *perfect gas*, and the equation $\frac{pv}{T} = R$, is called the *characteristic equation of a state of a perfect gas*. The constant R is called the *gas constant*. Each perfect gas has a different gas constant.

Units of R are Nm/kg K or kJ/kg K.

Usually, the characteristic equation is written as

$$pv = RT \qquad ...(1.1)$$

or for m kg, occupying V m^3

$$pV = mRT \qquad ...(1.2)$$

— The characteristic equation in *another form*, can be derived by using kilogram-mole as a unit.

The *kilogram-mole* is defined as a quantity of a gas equivalent to M kg of the gas, where M is the molecular weight of the gas (*e.g.* since the molecular weight of oxygen is 32, then 1 kg mole of oxygen is equivalent to 32 kg of oxygen).

Copyrighted material

For More Visit:www.LearnEngineering.in

As per definition of the kilogram-mole, for m kg of a gas, we have

$$m = nM \quad ...(1.3)$$

where n = Number of moles.

Note. Since the standard of mass is the kg, kilogram-mole will be written simply as mole.

Substituting for m from Eqn. (1.3) in Eqn. (1.2) gives

$$pV = nMRT$$

or

$$MR = \frac{pV}{nT}$$

According to *Avogadro's hypothesis* the volume of 1 mole of any gas is the same as the volume of 1 mole of any other gas, when the gases are at the same temperature and pressure. Therefore, $\frac{V}{n}$ is the same for all gases at the same value of p and T. That is the quantity $\frac{pV}{nT}$ is a *constant* for all gases. This constant is called *universal gas constant*, and is given the symbol, R_0.

i.e.,

$$MR = R_0 = \frac{pV}{nT}$$

or

$$pV = nR_0T \quad ...(1.4)$$

Since $MR = R_0$, then

$$R = \frac{R_0}{M} \quad ...(1.5)$$

It has been found experimentally that the volume of 1 mole of any prefect gas at 1 bar and 0°C is approximately 22.71 m³.

Therefore from Eqn. (1.4),

$$R_0 = \frac{pV}{nT} = \frac{1 \times 10^5 \times 22.71}{1 \times 273.15}$$

$$= 8314.3 \text{ Nm/mole K}$$

Using Eqn. (1.5), the gas constant for any gas can be found when the molecular weight is known.

Example. For oxygen which has a molecular weight of 32, the gas constant

$$R = \frac{R_0}{M} = \frac{8314}{32} = 259.8 \text{ Nm/kg K}.$$

1.17.2. Specific Heats

— The specific heat of a solid or liquid is usually defined as the *heat required to raise unit mass through one degree temperature rise.*

— For small quantities, we have

$$dQ = mcdT$$

where m = Mass

c = Specific heat

dT = Temperature rise.

For a gas there are an infinite number of ways in which heat may be added between any two temperatures, and hence a *gas could have an infinite number of specific heats.* However, only two specific heats for gases are defined.

Specific heat at constant volume, c_v

and *Specific heat at constant pressure,* c_p.

Copyrighted material

For More Visit:www.LearnEngineering.in

We have

$dQ = m\,c_p\,dT$ For a reversible non-flow process at *constant pressure* ...(1.6)

and $dQ = m\,c_v\,dT$ For a reversible non-flow process at *constant volume* ...(1.7)

The values of c_p and c_v, for a perfect gas, are constant for any one gas at all pressures and temperatures. Hence, integrating Eqns. (1.6) and (1.7), we have

Flow of heat in a reversible constant pressure process

$$= mc_p\,(T_2 - T_1) \quad ...(1.8)$$

Flow of heat in a reversible constant volume process

$$= mc_v\,(T_2 - T_1) \quad ...(1.9)$$

In case of *real gases*, c_p and c_v *vary with temperature*, but a suitable *average value* may be used for most practical purposes.

1.17.3. Joule's Law

Joule's law states as follows :

"The internal energy of a perfect gas is a function of the absolute temperature only."

i.e., $u = f(T)$

To evaluate this function let 1 kg of a perfect gas be heated at constant volume.

According to non-flow energy equation,

$$dQ = du + dW$$

$dW = 0$, since volume remains constant

$\therefore$ $dQ = du$

At constant volume for a perfect gas, from Eqn. (1.7), for 1 kg

$$dQ = c_v dT$$

$\therefore$ $dQ = du = c_v dT$

and integrating $u = c_v\,T + K$, K being constant.

According to Joule's law $u = f(T)$, which means that internal energy varies linearly with absolute temperature. Internal energy can be made zero at any arbitrary reference temperature. For a perfect gas it can be assumed that $u = 0$ when $T = 0$, hence constant K is zero.

i.e. Internal energy, $u = c_v\,T$ for a perfect gas ...(1.10)

or For mass m, of a prefect gas

Internal energy, $U = mc_v\,T$ ...(1.11)

For a perfect gas, in any process between states 1 and 2, we have from Eqn. (1.11)

Gain in internal energy,

$$U_2 - U_1 = mc_v\,(T_2 - T_1) \quad ...(1.12)$$

Eqn. (1.12) gives the gains of internal energy for a perfect gas between two states *for any process, reversible* or *irreversible.*

1.17.4. Relationship Between Two Specific Heats

Consider a perfect gas being heated at constant pressure from T_1 to T_2.

According to non-flow equation,

$$Q = (U_2 - U_1) + W$$

Also for a perfect gas,

$$U_2 - U_1 = mc_v\,(T_2 - T_1)$$

$$Q = mc_v\,(T_2 - T_1) + W$$

Copyrighted material

For More Visit:www.LearnEngineering.in

In a constant pressure process, the work done by the fluid,

$$W = p(V_2 - V_1)$$

$$= mR(T_2 - T_1) \qquad \left[\because \begin{array}{l} p_1V_1 = mRT_1 \\ p_2V_2 = mRT_2 \\ p_1 = p_2 = p \text{ in this case} \end{array}\right]$$

On substituting $\quad Q = mc_v\,(T_2 - T_1) + mR\,(T_2 - T_1) = m(c_v + R)\,(T_2 - T_1)$

But for a constant pressure process,

$$Q = mc_p\,(T_2 - T_1)$$

By equating the two expressions, we have

$$m(c_v + R)(T_2 - T_1) = mc_p(T_2 - T_1)$$

$$\therefore \qquad c_v + R = c_p$$

or

$$c_p - c_v = R \qquad \text{...(1.13)}$$

Dividing both sides by c_v, we get

$$\frac{c_p}{c_v} - 1 = \frac{R}{c_v}$$

$$\therefore \qquad c_v = \frac{R}{\gamma - 1} \qquad \text{...[1.13 (a)]}$$

(where $\gamma = c_p/c_v$)

Similarly, dividing both sides by c_p, we get

$$c_p = \frac{\gamma R}{\gamma - 1} \qquad \text{...[1.13 (b)]}$$

$$\left[\begin{array}{l} \text{In M.K.S. units}: c_p - c_v = \frac{R}{J}; c_v = \frac{R}{J(\gamma-1)}, c_p = \frac{\gamma R}{(\gamma-1)J} \\ \text{In SI units the value of } J \text{ is unity.} \end{array}\right]$$

1.17.5. Enthalpy

— One of the fundamental quantities which occur invariably in thermodynamics is the sum of internal energy (u) and pressure volume product (pv). This sum is called **Enthalpy** (h).

i.e., $\qquad h = u + pv \qquad$ ...(1.14)

— The enthalpy of a fluid is the property of the fluid, since it consists of the sum of a property and the product of the two properties. Since enthalpy is a property like internal energy, pressure, specific volume and temperature, it can be introduced into any problem whether the process is a flow or a non-flow process.

The total enthalpy of mass, m, of a fluid can be

$$H = U + pV, \text{ where } H = mh.$$

For a *perfect gas*,

Referring equation (1.14),

$$h = u + pv$$

$$= c_vT + RT \qquad [\because \quad pv = RT]$$

$$= (c_v + R)T$$

$$= c_pT \qquad [\because \quad c_p = c_v + R]$$

i.e.,

$$h = c_pT$$

and

$$H = mc_pT.$$

(Note that, since it has been assumed that $u = 0$ at $T = 0$, then $h = 0$ at $T = 0$).

Copyrighted material

For More Visit:www.LearnEngineering.in

1.17.6. Ratio of Specific Heats

The ratio of specific heat at constant pressure to the specific heat at constant volume is given by the symbol γ (gamma).

i.e.,
$$\gamma = \frac{c_p}{c_v} \qquad ...(1.15)$$

Since $c_p = c_v + R$, it is clear that c_p must be *greater* than c_v for any perfect gas. It follows, therefore, that the ratio, $\frac{c_p}{c_v} = \gamma$ is *always greater than unity.*

In general, the approximate values of γ are as follows :

For *monoatomic* gases such as *argon, helium* = 1.6.

For *diatomic* gases such as *carbon monoxide, hydrogen, nitrogen* and *oxygen* = 1.4.

For triatomic gases such as *carbondioxide* and *sulphur dioxide* = 1.3.

For some hydro-carbons the value of γ is quite low.

[*e.g.*, for ethane $\gamma = 1.22$, and for isobutane $\gamma = 1.11$]

Table 1.1. Summary of Processes for Perfect Gas (Unit mass)

Process	*Index* n	*Heat added*	$\int_1^2 pdv$	*p, v, T relations*	*Specific heat, c*
Constant pressure	$n = 0$	$c_p(T_2 - T_1)$	$p(v_2 - v_1)$	$\frac{T_2}{T_1} = \frac{v_2}{v_1}$	c_p
Constant volume	$n = \infty$	$c_v(T_2 - T_1)$	0	$\frac{T_1}{T_2} = \frac{p_1}{p_2}$	c_v
Constant temperature	$n = 1$	$p_1v_1 \log_e \frac{v_2}{v_1}$	$p_1v_1 \log_e \frac{v_2}{v_1}$	$p_1v_1 = p_2v_2$	∞
Reversible adiabatic	$n = \gamma$	0	$\frac{p_1v_1 - p_2v_2}{\gamma - 1}$	$p_1v_1^\gamma = p_2v_2^\gamma$ $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1}$ $= \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$	0
Polytropic	$n = n$	$c_n(T_2 - T_1)$ $= c_v\left(\frac{\gamma - n}{1 - n}\right) \times (T_2 - T_1)$ $= \frac{\gamma - n}{\gamma - 1} \times$ work done (non-flow)	$\frac{p_1v_1 - p_2v_2}{n - 1}$	$p_1v_1^n = p_2v_2^n$ $\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{n-1}$ $= \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$	$c_n = c_v\left(\frac{\gamma - n}{1 - n}\right)$

Note. Equations must be used keeping dimensional consistence.

Copyrighted material

For More Visit:www.LearnEngineering.in

1.18. STEADY FLOW ENERGY EQUATION (S.F.E.E.)

In many practical problems, the rate at which the fluid flows through a machine or piece of apparatus is constant. This type of flow is called *steady flow.*

Assumptions :

The following *assumptions* are made in the system analysis :

(*i*) The mass flow through the system remains constant.

(*ii*) Fluid is uniform in composition.

(*iii*) The only interaction between the system and surroundings are work and heat.

(*iv*) The state of fluid at any point remains constant with time.

(*v*) In the analysis only potential, kinetic and flow energies are considered.

Fig. 1.11 shows a schematic flow process for an open system. An open system is one in which both mass and energy may cross the boundaries. A wide interchange of energy may take place within an open system. Let the system be an automatic engine with the inlet manifold at the first state point and exhaust pipe as the second point. There would be an interchange of chemical energy in the fuel, kinetic energy of moving particles, internal energy of gas and heat transferred and shaft work within the system. From Fig. 1.11 it is obvious that if there is no variation of flow of mass or energy with time across the boundaries of the system the steady flow will prevail. The conditions may pass through the cyclic or non-cyclic changes within the system. As a result the mass entering the system equals the mass leaving, also energy entering the system equals energy leaving.

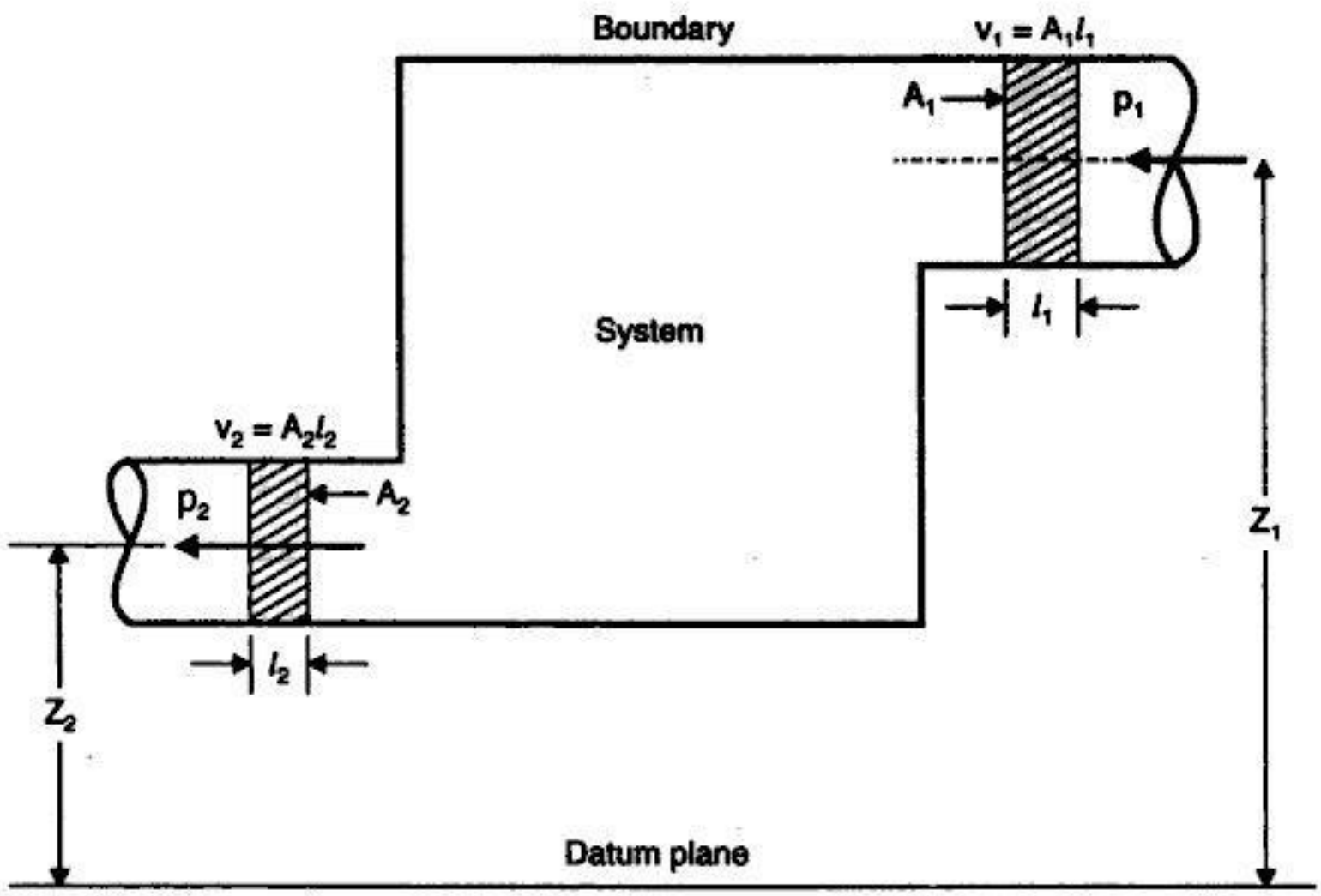


Fig. 1.11

Copyrighted material

For More Visit:www.LearnEngineering.in

The steady flow equation can be expressed as follows :

$$u_1 + \frac{C_1^2}{2} + Z_1 g + p_1 v_1 + Q = u_2 + \frac{C_2^2}{2} + Z_2 g + p_2 v_2 + W \quad ...(1.16)$$

$$(u_1 + p_1 v_1) + \frac{C_1^2}{2} + Z_1 g + Q = (u_2 + p_2 v_2) + \frac{C_2^2}{2} + Z_2 g + W$$

$$h_1 + \frac{C_1^2}{2} + Z_1 g + Q = h_2 + \frac{C_2^2}{2} + Z_2 g + W \quad [\because \ h = u + pv]$$

If Z_1 and Z_2 are neglected, we get

$$h_1 + \frac{C_1^2}{2} + Q = h_2 + \frac{C_2^2}{2} + W \quad ...[1.16\ (a)]$$

where Q = Heat supplied (or entering the boundary) per kg of fluid ;
W = Work done by (or work coming out of the boundary) 1 kg of fluid ;
C = Velocity of fluid ;
Z = Height above datum ;
p = Pressure of the fluid ;
u = Internal energy per kg of fluid ;
pv = Energy required for 1 kg of fluid.

This equation is applicable to any medium in any steady flow. It is applicable not only to rotary machines such as centrifugal fans, pumps and compressors but also to reciprocating machines such as steam engines.

In a steady flow the rate of mass flow of fluid at any section is the same as at any other section. Consider any section of cross-sectional area A, where the fluid velocity is C, the rate of volume flow past the section is CA. Also, since mass flow is volume flow divided by specific volume,

$$\text{Mass flow rate}, \dot{m} = \frac{CA}{v} \quad ...(1.17)$$

(where v = *specific volume* at the section)

This equation is known as the **continuity of mass equation.**

With reference to Fig. 1.11.

$$\therefore \quad \dot{m} = \frac{C_1 A_1}{v_1} = \frac{C_2 A_2}{v_2} \quad ...[1.17\ (a)]$$

1.18.1. Energy Relations for Flow Process

The energy equation (m kg of fluid) for a steady flow system is given as follows :

$$m\left(u_1 + \frac{C_1^2}{2} + Z_1 g + p_1 v_1\right) + Q = m\left(u_2 + \frac{C_2^2}{2} + Z_2 g + p_2 v_2\right) + W$$

i.e.,

$$Q = m\left[(u_2 - u_1) + (Z_2 g - Z_1 g) + \left(\frac{C_2^2}{2} - \frac{C_1^2}{2}\right) + (p_2 v_2 - p_1 v_1)\right] + W$$

i.e.,

$$Q = m\left[(u_2 - u_1) + g(Z_2 - Z_1) + \left(\frac{C_2^2 - C_1^2}{2}\right) + (p_2 v_2 - p_1 v_1)\right] + W$$

Copyrighted material

For More Visit:www.LearnEngineering.in

$$= \Delta U + \Delta PE + \Delta KE + \Delta (pv) + W$$

where $\Delta U = m (u_2 - u_1)$

$$\Delta PE = mg (Z_2 - Z_1)$$

$$\Delta KE = m \left(\frac{C_2^2 - C_1^2}{2} \right)$$

$$\Delta pv = m(p_2 v_2 - p_1 v_1)$$

$$\therefore \quad Q - \Delta U = [\Delta PE + \Delta KE + \Delta(pv) + W] \quad ...(1.18)$$

For non-flow process, $Q = \Delta U + W = \Delta U + \int_1^2 pdV$

i.e., $$Q - \Delta U = \int_1^2 pdV \quad ...(1.19)$$

1.19. LIMITATIONS OF FIRST LAW OF THERMODYNAMICS

It has been observed that *energy can flow* from a system in the form of *heat* or *work*. The first law of thermodynamics sets no limit to the amount of the total energy of a system which can be caused to flow out as work. A limit is imposed, however, as a result of the principle enunciated in the second law of thermodynamics which states that heat will flow naturally from one energy reservoir to another at a lower temperature, but not in opposite direction without assistance. This is very important because a heat engine operates between two energy reservoirs at different temperatures.

Further the first law of thermodynamics *establishes equivalence between the quantity of heat used and the mechanical work but does not specify the conditions under which conversion of heat into work is possible, neither the direction in which heat transfer can take place.* This gap has been *bridged* by the second law of thermodynamics.

1.20. PERFORMANCE OF HEAT ENGINE AND REVERSED HEAT ENGINE

Refer Fig. 1.12 (*a*). A *heat engine* is used to produce the maximum work transfer from a given positive heat transfer. The measure of success is called the *thermal efficiency* of the engine and is defined by the ratio :

$$\text{Thermal efficiency, } \eta_{th} = \frac{W}{Q_1} \quad ...(1.20)$$

where W = Net work transfer from the engine, and

Q_1 = Heat transfer to engine.

For a *reversed heat engine* [Fig. 1.12 (*b*)] acting as a *refrigerator* when the purpose is to achieve the maximum heat transfer from the cold reservoir, the measure of success is called the co-efficient of performance (C.O.P.). It is defined by the ratio :

$$\text{Co-efficient of performance, } (\text{C.O.P.})_{ref.} = \frac{Q_2}{W} \quad ...(1.21)$$

where Q_2 = Heat transfer *from cold reservoir*

W = The net work transfer to the refrigerator.

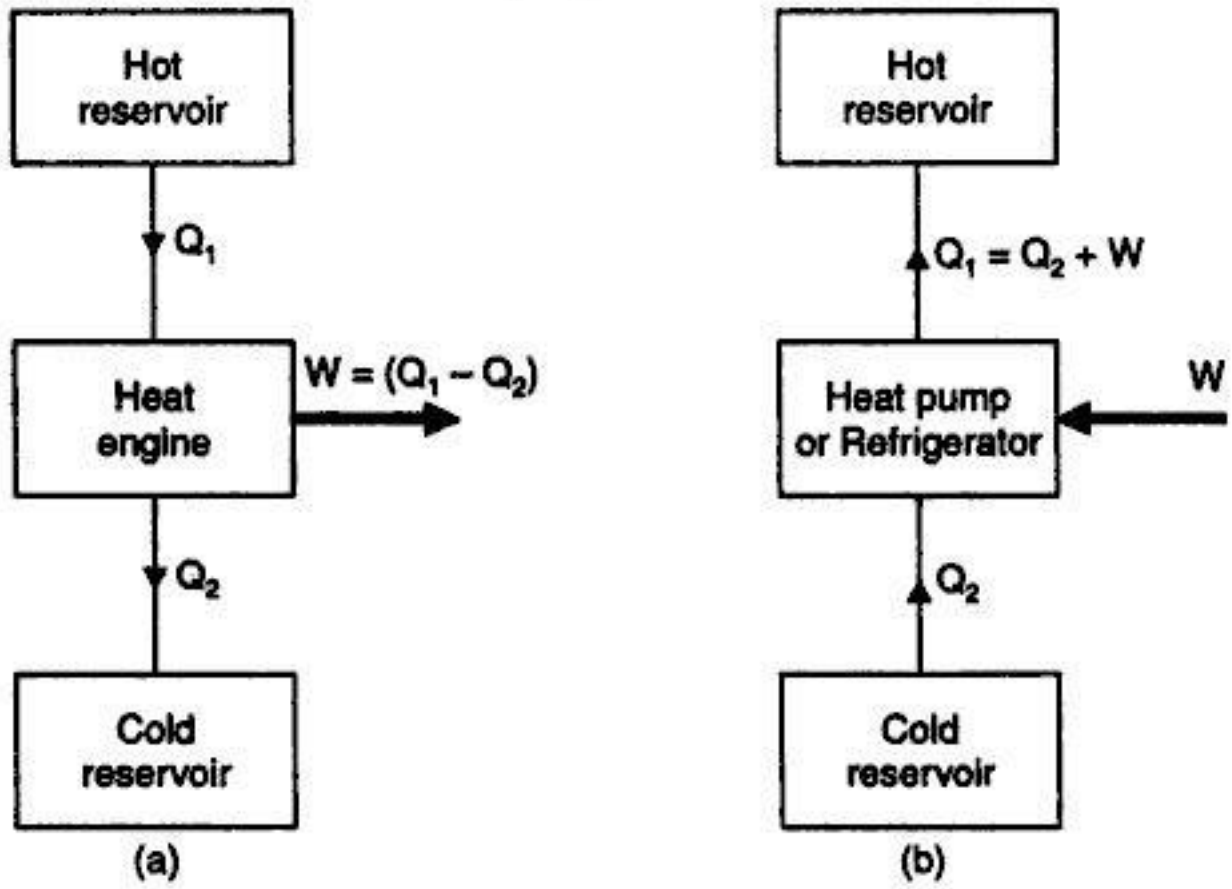
For a **reversed heat engine** [Fig. 1.12 (*b*)] acting as a *heat pump*, the measure of success is again called the *co-efficient of performance*. It is defined by the ratio :

Copyrighted material

For More Visit:www.LearnEngineering.in

$$\text{Co-efficient of performance, } (C.O.P.)_{heat\ pump} = \frac{Q_1}{W} \quad ...(1.22)$$

where Q_1 = Heat transfer *to hot reservoir*
W = Net work transfer to the heat pump.



(*a*) Heat engine (*b*) Heat pump or refrigerator.

Fig. 1.12

In all the above three cases application of the first law gives the relation $Q_1 - Q_2 = W$, and this can be used to rewrite the expressions for thermal efficiency and co-efficient of performance solely in terms of the heat transfers.

$$\eta_{th} = \frac{Q_1 - Q_2}{Q_1} \quad ...(1.23)$$

$$(C.O.P.)_{ref} = \frac{Q_2}{Q_1 - Q_2} \quad ...(1.24)$$

$$(C.O.P.)_{heat\ pump} = \frac{Q_1}{Q_1 - Q_2} \quad ...(1.25)$$

It may be seen that η_{th} is *always less than unity* and $(C.O.P.)_{heat\ pump}$ is *always greater than unity*.

1.21. STATEMENTS OF SECOND LAW OF THERMODYNAMICS

The second law of thermodynamics has been enunciated meticulously by Clausius, Kelvin and Planck in slightly different words although both statements are basically identical. Each statement is based on an *irreversible process*. The *first considers transformation of heat between two thermal reservoirs* while the *second considers the transformation of heat into work*.

1.21.1. Clausius Statement

"It is impossible for a self acting machine working in a cyclic process unaided by any external agency, to convey heat from a body at a lower temperature to a body at a higher temperature".

In other words, heat of, itself, cannot flow from a colder to a hotter body.

Copyrighted material

For More Visit:www.LearnEngineering.in

1.21.2. Kelvin-Planck Statement

"It is impossible to construct an engine, which while operating in a cycle produces no other effect except to extract heat from a single reservoir and do equivalent amount of work".

Although the Clausius and Kelvin-Planck statements appear to be different, they are really equivalent in the sense that a *violation of either statement implies violation of other.*

1.22. ENTROPY

1.22.1. Introduction

In heat engine theory, the term entropy plays a vital role and leads to important results which by other methods can be obtained much more laboriously.

It may be noted that all heat is not equally valuable for converting into work. Heat that is supplied to a substance at high temperature has a greater possibility of conversion into work than heat supplied to a substance at a lower temperature.

*"**Entropy** is a function of a quantity of heat which shows the possibility of conversion of that heat into work. The increase in entropy is small when heat is added at a high temperature and is greater when heat addition is made at a lower temperature. Thus for maximum entropy, there is minimum availability for conversion into work and for minimum entropy there is maximum availability for conversion into work."*

The entropy attains its maximum value when the system reaches a stable equilibrium state from a non-equilibrium state. This is the state of maximum disorder and is one of maximum thermodynamic probability.

1.22.2. Temperature-Entropy Diagram

If entropy is plotted horizontally and absolute temperature vertically, the diagram so obtained is called *temperature entropy* (*T-s*) diagram. Such a diagram is shown in Fig. 1.13. If working

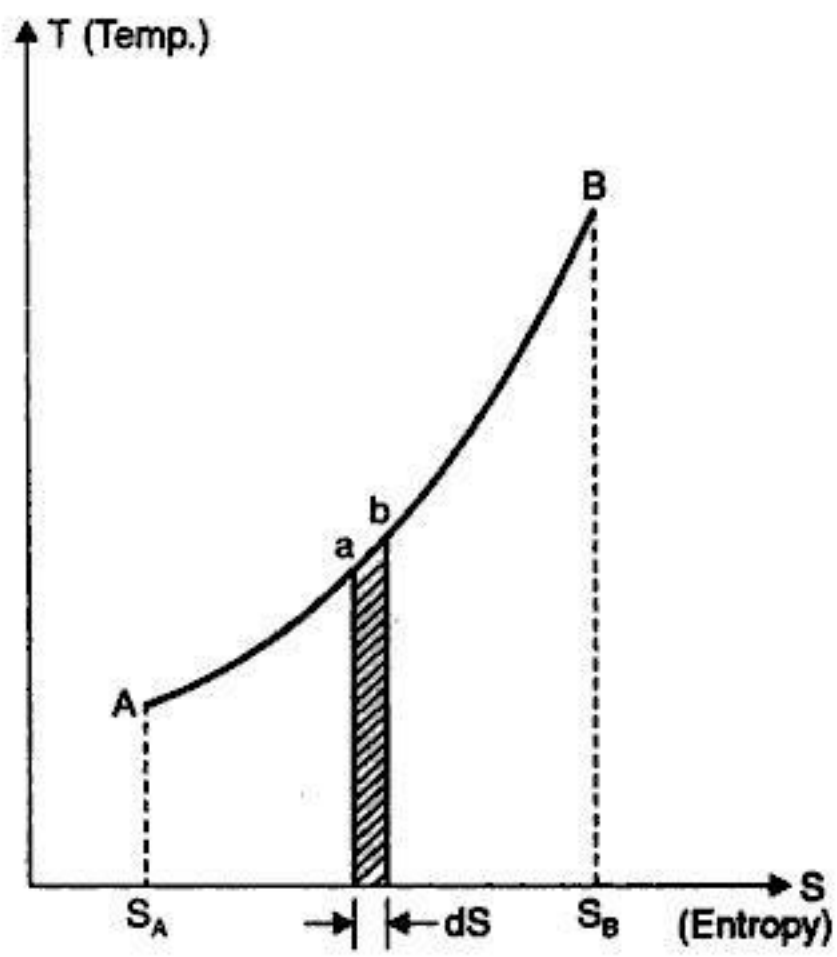


Fig. 1.13. Temperature-entropy diagram.

Copyrighted material

For More Visit:www.LearnEngineering.in

For More Visit:www.LearnEngineering.in

fluid receives a small amount of heat dQ in an elementary portion ab of an operation AB when temperature is T, and if dQ is represented by the shaded area of which T is the mean ordinate, the width of the figure must be $\frac{dQ}{T}$. This is called *'increment of entropy'* and is denoted by dS. The total heat received by the operation will be given by the area under the curve AB and $(S_B - S_A)$ will be corresponding increase of entropy.

From above we conclude that :

$$\text{Entropy change,} \quad dS = \frac{\text{Heat Change } (Q)}{\text{Absolute temperature } (T)}.$$

"Entropy may also be defined as the thermal property of a substance which remains constant when substance is expanded or compressed adiabatically in a cylinder".

Note. 's' stands for specific entropy whereas 'S' means total entropy (*i.e.*, $S = ms$).

1.22.3. Characteristics of Entropy

The *characteristics of entropy* in a summarised form are given below :

1. It increases when heat is supplied irrespective of the fact whether temperature changes or not.
2. It decreases when heat is removed whether temperature changes or not.
3. It remains unchanged in all adiabatic frictionless processes.
4. It increases if temperature of heat is lowered without work being done as in a throttling process.

Table 1.2. Summary of Formulae

S. No.	*Process*	*Change of entropy (per kg)*
1.	General case	(*i*) $c_v \log_e \frac{T_2}{T_1} + R \log_e \frac{v_2}{v_1}$ (in terms of T and v)
		(*ii*) $c_v \log_e \frac{p_2}{p_1} + c_v \log_e \frac{v_2}{v_1}$ (in terms of p and v)
		(*iii*) $c_p \log_e \frac{T_2}{T_1} - R \log_e \frac{p_2}{p_1}$ (in terms of T and p)
2.	Constant volume	$c_v \log_e \frac{T_2}{T_1}$
3.	Constant pressure	$c_p \log_e \frac{T_2}{T_1}$
4.	Isothermal	$R \log_e \frac{v_2}{v_1}$
5.	Adiabatic	Zero
6.	Polytropic	$c_v \left(\frac{n-\gamma}{n-1}\right) \log_e \frac{T_2}{T_1}$

1.23. THE THIRD LAW OF THERMODYNAMICS

The third law of thermodynamics is stated as follows :

"The entropy of all perfect crystalline solids is zero at absolute zero temperature".

Copyrighted material

For More Visit:www.LearnEngineering.in

The third law of thermodynamics, often referred to as **Nernst law,** provides the basis for the calculations of absolute entropies of substances.

According to this law, if the entropy is zero at $T = 0$, the absolute entropy $s_{ab.}$ of a substance at any temperature T and pressure p is expressed by the expression

$$s_{ab.} = \int_0^{T_s = T_{f_1}} c_{ps} \frac{dT}{T} + \frac{h_{sf}}{T_s} + \int_{T_s}^{T_{f_2} = T_g} c_{pf} \frac{dT}{T} + \frac{h_{fg}}{T_g} \int_{T_g}^{T} c_{pg} \frac{dT}{T} \quad ...(1.26)$$

where $T_s = T_{f_1} = T_{sf} = T_{sat}$ ...for fusion,

$T_{f_2} = T_g = T_{fg} = T_{sat}$ ...for vaporisation,

c_{ps}, c_{pf}, c_{pg} = Constant pressure specific heats for solids, liquids and gas, and

h_{sf}, h_{fg} = Latent heats of fusion and vaporisation.

Thus by putting $s = 0$ at $T = 0$, one may integrate zero kelvin and standard state of 298.15 K and 1 atm., and find the entropy difference.

Further, it can be shown that the entropy of a crystalline substance at $T = 0$ is not a function of pressure, *viz.*, $\left(\frac{\partial s}{\partial p}\right)_{T=0} = 0$.

However, at temperature above absolute zero, the entropy is a function of pressure also.

1.24. AVAILABLE AND UNAVAILABLE ENERGY

There are many forms in which an energy can exist. But even under ideal conditions all these forms cannot be converted completely into work. This indicates that energy has two parts :

— Available part.

— Unavailable part.

'Available energy' is the *maximum portion of energy which could be converted into useful work by ideal processes which reduce the system to a dead state* (a state in equilibrium with the earth and its atmosphere). Because there can be only one value for maximum work which the system alone could do while descending to its dead state, it follows immediately that *'Available energy' is a property.*

A system which has a pressure difference from that of surroundings, work can be obtained from an expansion process, and if the system has a different temperature, heat can be transferred to a cycle and work can be obtained. But when the temperature and pressure becomes equal to that of the earth, transfer of energy ceases, and although the system contains internal energy, this energy is *unavailable.*

Summarily available energy denote, the latent capability of energy to do work, and in this sense it can be applied to energy in the system or in the surroundings.

The theoretical maximum amount of work which can be obtained from a system at any state p_1 and T_1 when operating with a reservoir at the constant pressure and temperature p_0 and T_0 is called **'availability'.**

Copyrighted material

For More Visit:www.LearnEngineering.in

HIGHLIGHTS

1. *Thermodynamics* is an axiomatic science which deals with the relations among heat, work and properties of systems which are in equilibrium. It basically entails four laws or axioms known as *Zeroth, First, Second* and *Third* law of thermodynamics.
2. A *system* is a finite quantity of matter or a prescribed region of space.

   A system may be a *closed, open* or *isolated* system.
3. A *phase* is a quantity of matter which is homogeneous throughout in chemical composition and physical structure.
4. A *homogeneous system* is one which consists of a *single phase*.
5. A *heterogeneous system* is one which consists of *two or more phases*.
6. A *pure substance* is one that has a homogeneous and invariable chemical composition even though there is a change of phase.
7. A system is in *thermodynamic equilibrium* if temperature and pressure at all points are same ; there should be no *velocity gradient*.
8. A *property of a system* is a characteristic of the system which depends upon its state, but not upon how the state is reached.

   Intensive properties do not depend on the mass of the system.

   Extensive properties depend on the mass of the system.
9. *State* is the condition of the system at an instant of time as described or measured by its properties. Or each unique condition of a system is called a state.
10. A *process* occurs when the system undergoes a change in state or an energy transfer takes place at a steady state.
11. Any process or series of processes whose end states are identical is termed a *cycle*.
12. The *pressure* of a system is the force exerted by the system on unit area of boundaries. Vacuum is defined as the absence of pressure.
13. A *reversible process* is one which can be stopped at any stage and reversed so that the system and surroundings are exactly restored to their initial states.

    An *irreversible process* is one in which heat is transferred through a finite temperature.
14. Zeroth law of termodynamics states that if two systems are each equal in temperature to a third, they are equal in temperature to each other.
15. Infinite slowness is the characteristic feature of a quasi-static process. A quasi-static process is a succession of equilibrium states. It is also called a reversible process.
16. *Internal energy* is the heat energy stored in a gas. The internal energy of a perfect gas is a function of *temperature* only.
17. First law of thermodynamics states :

    — Heat and work are mutually convertible but since energy can neither be created nor destroyed, the total energy associated with an energy conversion remains constant.

    Or

    — No machine can produce energy without corresponding expenditure of energy, *i.e.* it is impossible to construct a perpetual motion machine of first kind.

    First law can be expressed as follows :

    $$Q = \Delta E + W$$

    $$Q = \Delta U + W$$ ... if electric, magnetic, chemical energies are absent and changes in potential and kinetic energies are neglected.

Copyrighted material

For More Visit:www.LearnEngineering.in

18. There can be no machine which would continuously supply mechanical work without some form of energy disappearing simultaneously. Such a fictitious machine is called a perpetual motion machine of the first kind, or in brief, PMM1. A PMM1 is thus impossible.

19. The energy of an isolated system is always constant.

20. In case of

(*i*) **Reversible constant volume process** (v = constant)

$$\Delta u = c_v(T_2 - T_1)\,;\; W = 0\,;\; Q = c_v\,(T_2 - T_1)$$

(*ii*) **Reversible constant pressure process** (p = constant)

$$\Delta u = c_v(T_2 - T_1)\,;\; W = p(v_2 - v_1)\,;\; Q = c_p\,(T_2 - T_1)$$

(*iii*) **Reversible temperature or isothermal process** (pv = constant)

$$\Delta u = 0,\; W = p_1V_1 \log_e r,\; Q = W$$

where r = expansion or compression ratio.

(*iv*) **Reversible adiabatic process** (pv^γ = constant)

$$\pm \Delta u = \mp\, W = \frac{R(T_1 - T_2)}{\gamma - 1}\;;\; Q = 0\,;\; \frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma - 1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma - 1}{\gamma}}$$

(v) **Polytropic reversible process** (pv^n = constant)

$$\Delta u = c_v\,(T_2 - T_1)\,;\; W = \frac{R(T_1 - T_2)}{n - 1}\;;\; Q = \Delta u + W\,;$$

and $$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{n-1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} \quad \text{and} \quad Q = \left(\frac{\gamma - n}{\gamma - 1}\right) \times W.$$

21. Steady flow equation can be expressed as follows :

$$u_1 + \frac{C_1^2}{2} + Z_1 g + p_1 v_1 + Q = u_2 + \frac{C_2^2}{2} + Z_2 g + p_2 v_2 + W \qquad ...(i)$$

or $$h_1 + \frac{C_1^2}{2} + Q = h_2 + \frac{C_2^2}{2} + W, \text{ neglecting } Z_1 \text{ and } Z_2 \qquad ...(ii)$$

where Q = Heat supplied per kg of fluid ; W = Work done by 1 kg of fluid ;
C = Velocity of fluid ; Z = Height above datum ;
p = Pressure of the fluid ; u = Internal energy per kg of fluid ;
pv = Energy required per kg of fluid.

This equation is applicable to any medium in any steady flow.

22. **Clausius statement :**

"It is impossible for a self-acting machine working in a cyclic process, unaided by any external agency, to convey heat from a body at a lower temperature to a body at a higher temperature."

Kelvin-Planck statement :

"It is impossible to construct an engine, which while operating in a cycle produces no other effect except to extract heat from a single reservoir and do equivalent amount of work".

Although above statements of second law of thermodynamics appear to be different, they are really equivalent in the sense that violation of either statement implies violation of other.

23. Clausius inequality is given by,

$$\sum_{\text{Cycle}} \left(\frac{\delta Q}{T}\right) \le 0$$

Copyrighted material

For More Visit:www.LearnEngineering.in

"When a system performs a reversible cycle, then

$$\sum_{\text{Cycle}} \left(\frac{\delta Q}{T}\right) = 0,$$

but when the cycle is not reversible

$$\sum_{\text{Cycle}} \left(\frac{\delta Q}{T}\right) < 0."$$

24. **'Entropy'** is a function of a quantity of heat which shows the possibility of conversion of that heat into work. The increase in entropy is small when heat is added at a high temperature and is greater when heat addition is made at lower temperature. Thus for maximum entropy, there is a minimum availability for conversion into work and for minimum entropy there is maximum availability for conversion into work.

25. **The third law of thermodynamics** is stated as follows :
"The entropy of all perfect crystalline solids is zero at absolute zero temperature".

OBJECTIVE TYPE QUESTIONS

Choose the correct answer :

1. A definite area or space where some thermodynamic process takes place is known as
   (*a*) thermodynamic system (*b*) thermodynamic cycle
   (*c*) thermodynamic process (*d*) thermodynamic law.
2. An open system is one in which
   (*a*) heat and work cross the boundary of the system, but the mass of the working substance does not
   (*b*) mass of working substance crosses the boundary of the system but the heat and work do not
   (*c*) both the heat and work as well as mass of the working substances cross the boundary of the system
   (*d*) neither the heat and work nor the mass of the working substances cross the boundary of the system.
3. An isolated system
   (*a*) is a specified region where transfer of energy and/or mass take place
   (*b*) is a region of constant mass and only energy is allowed to cross the boundaries
   (*c*) cannot transfer either energy or mass to or from the surroundings
   (*d*) is one in which mass within the system is not necessarily constant
   (*e*) none of the above.
4. In an extensive property of a thermodynamic system
   (*a*) extensive heat is transferred (*b*) extensive work is done
   (*c*) extensive energy is utilised (*d*) all of the above
   (*e*) none of the above.
5. Which of the following is an intensive property of a thermodynamic system ?
   (*a*) Volume (*b*) Temperature
   (*c*) Mass (*d*) Energy.
6. Which of the following is the extensive property of a thermodynamic system ?
   (*a*) Pressure (*b*) Volume
   (*c*) Temperature (*d*) Density.
7. When two bodies are in thermal equilibrium with a third body they are also in thermal equilibrium with each other. This statement is called
   (*a*) Zeroth law of thermodynamics (*b*) First law of thermodynamics
   (*c*) Second law of thermodynamics (*d*) Kelvin-Planck's law.

Copyrighted material

For More Visit:www.LearnEngineering.in

8. The temperature at which the volume of a gas becomes zero is called
   (a) absolute scale of temperature (b) absolute zero temperature
   (c) absolute temperature (d) none of the above.
9. The value of one bar (in SI units) is equal to
   (a) 100 N/m² (b) 1000 N/m² (c) 1×10^4 N/m²
   (d) 1×10^5 N/m² (e) 1×10^6 N/m².
10. The absolute zero pressure will be
   (a) when molecular momentum of the system becomes zero
   (b) at sea level (c) at the temperature of – 273 K
   (d) under vacuum conditions (e) at the centre of the earth.
11. Absolute zero temperature is taken as
   (a) –273°C (b) 273°C
   (c) 237°C (d) –373°C.
12. Which of the following is correct ?
   (a) Absolute pressure = gauge pressure + atmospheric pressure
   (b) Gauge pressure = absolute pressure + atmospheric pressure
   (c) Atmospheric pressure = absolute pressure + gauge pressure
   (d) Absolute pressure = gauge pressure – atmospheric pressure.
13. The unit of energy in SI units is
   (a) Joule (J) (b) Joule metre (Jm)
   (c) Watt (W) (d) Joule/metre (J/m).
14. One watt is equal to
   (a) 1 Nm/s (b) 1 N/min (c) 10 N/s
   (d) 100 Nm/s (e) 100 Nm/m.
15. One joule (J) is equal to
   (a) 1 Nm (b) kNm
   (c) 10 Nm/s (d) 10 kNm/s.
16. The amount of heat required to raise the temperature of 1 kg of water through 1°C is called
   (a) specific heat at constant volume (b) specific heat at constant pressure
   (c) kilo calorie (d) none of the above.
17. The heating and expanding of a gas is called
   (a) thermodynamic system (b) thermodynamic cycle
   (c) thermodynamic process (d) thermodynamic law.
18. A series of operations, which take place in a certain order and restore the initial condition is known as
   (a) reversible cycle (b) irreversible cycle
   (c) thermodynamic cycle (d) none of the above.
19. The condition for the reversibility of a cycle is
   (a) the pressure and temperature of the working substance must not differ, appreciably, from those of the surroundings at any stage in the process
   (b) all the processes, taking place in the cycle of operation, must be extremely slow
   (c) the working parts of the engine must be friction free
   (d) there should be no loss of energy during the cycle of operation
   (e) all of the above (f) none of the above.
20. In an irreversible process, there is a
   (a) loss of heat (b) no loss of heat
   (c) gain of heat (d) no gain of heat.

Copyrighted material

For More Visit:www.LearnEngineering.in

For More Visit:www.LearnEngineering.in

21. The main cause of the irreversibility is
(*a*) mechanical and fluid friction (*b*) unrestricted expansion
(*c*) heat transfer with a finite temperature difference
(*d*) all of the above (*e*) none of the above.

22. According to kinetic theory of heat
(*a*) temperature should rise during boiling (*b*) temperature should fall during freezing
(*c*) at low temperature all bodies are in solid state
(*d*) at absolute zero there is absolutely no vibration of molecules
(*e*) none of the above.

23. A system comprising a single phase is called a
(*a*) closed system (*b*) open system (*c*) isolated system
(*d*) homogeneous system (*e*) heterogeneous system.

24. If all the variables of a stream are independent of time it is said to be in
(*a*) steady flow (*b*) unsteady flow (*c*) uniform flow
(*d*) closed flow (*e*) constant flow.

25. A control volume refers to
(*a*) a fixed region in space (*b*) a specified mass
(*c*) an isolated system (*d*) a reversible process only
(*e*) a closed system.

26. Internal energy of a perfect gas depends on
(*a*) temperature, specific heats and pressure (*b*) temperature, specific heats and enthalpy
(*c*) temperature, specific heats and entropy (*d*) temperature only.

27. In reversible polytropic process
(*a*) true heat transfer occurs (*b*) the entropy remains constant
(*c*) the enthalpy remains constant (*d*) the internal energy remains constant
(*e*) the temperature remains constant.

28. An isentropic process is always
(*a*) irreversible and adiabatic (*b*) reversible and isothermal
(*c*) frictionless and irreversible (*d*) reversible and adiabatic
(*e*) none of the above.

29. The net work done per kg of gas in a polytropic process is equal to

(*a*) $p_1 v_1 \log_e \frac{v_2}{v_1}$ (*b*) $p_1 (v_1 - v_2)$ (*c*) $p_2 \left(v_2 - \frac{v_1}{v_2} \right)$

(*d*) $\frac{p_1 v_1 - p_2 v_2}{n-1}$ (*e*) $\frac{p_2 v_1 - p_2 v_2}{n-1}$.

30. Steady flow occurs when
(*a*) conditions do not change with time at any point
(*b*) conditions are the same at adjacent points at any instant
(*c*) conditions change steadily with the time
(*d*) $\left(\frac{\partial v}{\partial t} \right)$ is constant.

31. A reversible process requires that
(*a*) there be no heat transfer (*b*) newton's law of viscosity be satisfied
(*c*) temperature of system and surroundings be equal
(*d*) there be no viscous or coloumb friction in the system
(*e*) heat transfer occurs from surroundings to system only.

Copyrighted material

For More Visit:www.LearnEngineering.in

32. The first law of thermodynamics for steady flow
(a) accounts for all energy entering and leaving a control volume
(b) is an energy balance for a specified mass of fluid
(c) is an expression of the conservation of linear momentum
(d) is primarily concerned with heat transfer.
(e) is restricted in its application to perfect gases.

33. The characteristic equation of gases $pV = mRT$ holds good for
(a) monoatomic gases (b) diatomic gas (c) real gases
(d) ideal gases (e) mixture of gases.

34. A gas which obeys kinetic theory perfectly is known as
(a) monoatomic gas (b) diatomic gas (c) real gas
(d) pure gas (e) perfect gas.

35. Work done in a free expansion process is
(a) zero (b) minimum (c) maximum
(d) positive (e) negative.

36. Which of the following is not a property of the system ?
(a) Temperature (b) Pressure (c) Specific volume
(d) Heat (e) None of the above.

37. In the polytropic process equation pv^n = constant, if $n = 0$, the process is termed as
(a) constant volume (b) constant pressure (c) constant temperature
(d) adiabatic (e) isothermal.

38. In the polytropic process equation pv^n = constant, if n is infinitely large, the process is termed as
(a) constant volume (b) constant pressure (c) constant temperature
(d) adiabatic (e) isothermal.

39. The processes or systems that do not involve heat are called
(a) isothermal processes (b) equilibrium processes (c) thermal processes
(d) steady processes (e) adiabatic processes.

40. In a reversible adiabatic process the ratio (T_1/T_2) is equal to

(a) $\left(\frac{p_1}{p_2}\right)^{\frac{\gamma-1}{\gamma}}$ (b) $\left(\frac{v_1}{v_2}\right)^{\frac{\gamma-1}{\gamma}}$

(c) $(v_1 v_2)^{\frac{\gamma-1}{2\gamma}}$. (d) $\left(\frac{v_2}{v_1}\right)^{\gamma}$.

41. In isothermal process
(a) temperature increases gradually (b) volume remains constant
(c) pressure remains constant (d) enthalpy change is maximum
(e) change in internal energy is zero.

42. During throttling process
(a) internal energy does not change (b) pressure does not change
(c) entropy does not change (d) enthalpy does not change
(e) volume change is negligible.

43. When a gas is to be stored, the type of compression that would be ideal is
(a) isothermal (b) adiabatic (c) polytropic
(d) constant volume (e) none of the above.

44. If a process can be stopped at any stage and reversed so that the system and surroundings are exactly restored to their initial states, it is known as
(a) adiabatic process (b) isothermal process (c) ideal process
(d) frictionless process (e) energyless process.

Copyrighted material

For More Visit:www.LearnEngineering.in

45. The state of a substance whose evaporation from its liquid state is complete, is known as
(a) vapour (b) perfect gas
(c) air (d) steam.

46. In SI units, the value of the universal gas constant is
(a) 0.8314 J/mole/K (b) 8.314 J/mole/K
(c) 83.14 J/mole/K (d) 831.4 J/mole/K
(e) 8314 J/mole/K.

47. When the gas is heated at constant pressure, the heat supplied
(a) increases the internal energy of the gas (b) increases the temperature of the gas
(c) does some external work during expansion (d) both (b) and (c)
(e) none of the above.

48. The gas constant (R) is equal to the
(a) sum of two specific heats (b) difference of two specific heats
(c) product of two specific heats (d) ratio of two specific heats.

49. The heat absorbed or rejected during a polytropic process is
(a) $\left(\frac{\gamma-n}{\gamma-1}\right)$ × work done (b) $\left(\frac{\gamma-n}{\gamma-1}\right)^2$ × work done
(c) $\left(\frac{\gamma-n}{\gamma-1}\right)^{1/2}$ × work done (d) $\left(\frac{\gamma-n}{\gamma-1}\right)^3$ × work done.

50. Second law of thermodynamics defines
(a) heat (b) work (c) enthalpy
(d) entropy (e) internal energy.

51. For a reversible adiabatic process, the change in entropy is
(a) zero (b) minimum (c) maximum
(d) infinite (e) unity.

52. For any reversible process, the change in entropy of the system and surroundings is
(a) zero (b) unity (c) negative
(d) positive (e) infinite.

53. For any irreversible process the net entropy change is
(a) zero (b) positive (c) negative
(d) infinite (e) unity.

54. The processes of a Carnot cycle are
(a) two adiabatic and two constant volume
(b) one constant volume and one constant pressure and two isentropics
(c) two adiabatics and two isothermals (d) two constant volumes and two isothermals
(e) two isothermals and two isentropics.

55. Isentropic flow is
(a) irreversible adiabatic flow (b) ideal fluid flow (c) perfect gas flow
(d) frictionless reversible flow (e) reversible adiabatic flow.

56. In a Carnot engine, when the working substance gives heat to the sink
(a) the temperature of the sink increases (b) the temperature of the sink remains the same
(c) the temperature of the source decreases
(d) the temperatures of both the sink and the source decrease
(e) changes depend on the operating conditions.

Copyrighted material

For More Visit:www.LearnEngineering.in

57. If the temperature of the source is increased, the efficiency of the Carnot engine
(a) decreases (b) increases
(c) does not change (d) will be equal to the efficiency of a practical engine
(e) depends on other factors.

58. The efficiency of an ideal Carnot engine depends on
(a) working substance (b) on the temperature of the source only
(c) on the temperature of the sink only
(d) on the temperatures of both the source and the sink
(e) on the construction of engine.

59. The efficiency of a Carnot engine using an ideal gas as the working substance is
(a) $\frac{T_1 - T_2}{T_1}$ (b) $\frac{T_1}{T_1 - T_2}$ (c) $\frac{T_1 T_2}{T_1 - T_2}$
(d) $\frac{T_1 - T_2}{T_1 T_2}$ (e) $\frac{T_2(T_1 - T_2)}{T_1(T_1 + T_2)}$.

60. In a reversible cycle, the entropy of the system
(a) increases (b) decreases
(c) does not change (d) first increases and then decreases
(e) depends on the properties of working substance.

61. A frictionless heat engine can be 100% efficient only if its exhaust temperature is
(a) equal to its input temperature (b) less than its input temperature
(c) 0°C (d) 0°K (e) – 100°C.

62. Kelvin-Planck's law deals with
(a) conservation of energy (b) conservation of heat (c) conservation of mass
(d) conversion of heat into work (e) conversion of work into heat.

63. Which of the following statements is correct according to Clausius statement of second law of thermodynamics ?
(a) It is impossible to transfer heat from a body at a lower temperature to a body at a higher temperature
(b) It is impossible to transfer heat from a body at a lower temperature to a body at a higher temperature, without the aid of an external source.
(c) It is possible to transfer heat from a body at a lower temperature to a body at a higher temperature by using refrigeration cycle
(d) None of the above.

64. According to Kelvin-Planck's statement of second law of thermodynamics
(a) It is impossible to construct an engine working on a cyclic process, whose sole purpose is to convert heat energy into work
(b) It is possible to construct an engine working on a cyclic process, whose sole purpose is to convert the heat energy into work
(c) It is impossible to construct a device which while working in a cyclic process produces no effect other than the transfer of heat from a colder body to a hotter body
(d) When two dissimilar metals are heated at one end and cooled at the other, the e.m.f. developed is proportional to the difference of their temperatures at the two end.
(e) None of the above.

65. The property of a working substance which increases or decreases as the heat is supplied or removed in a reversible manner is known as
(a) enthalpy (b) internal energy
(c) entropy (d) external energy.

Copyrighted material

For More Visit:www.LearnEngineering.in

66. The entropy may be expressed as a function of

(*a*) pressure and temperature (*b*) temperature and volume

(*c*) heat and work (*d*) all of the above

(*e*) none of the above.

67. The change of entropy, when heat is absorbed by the gas is

(*a*) positive (*b*) negative (*c*) positive or negative.

68. Which of the following statements is *correct* ?

(*a*) The increase in entropy is obtained from a given quantity of heat at a low temperature

(*b*) The change in entropy may be regarded as a measure of the rate of the availability of heat for transformation into work

(*c*) The entropy represents the maximum amount of work obtainable per degree drop in temperature

(*d*) All of the above.

69. The condition for the reversibility of a cycle is

(*a*) the pressure and temperature of working substance must not differ, appreciably from those of the surroundings at any stage in the process

(*b*) all the processes taking place in the cycle of operation, must be extremely slow

(*c*) the working parts of the engine must be friction free

(*d*) there should be no loss of energy during the cycle of operation

(*e*) all of the above.

70. In an irreversible process there is a

(*a*) loss of heat (*b*) no loss of work

(*c*) gain of heat (*d*) no gain of heat.

71. The main cause for the irreversibility is

(*a*) mechanical and fluid friction (*b*) unrestricted expansion

(*c*) heat transfer with a finite temperature difference

(*d*) all of the above.

72. The efficiency of the Carnot cycle may be increased by

(*a*) increasing the highest temperature (*b*) decreasing the highest temperature

(*c*) increasing the lowest temperature (*d*) decreasing the lowest temperature

(*e*) keeping the lowest temperature constant.

73. Which of the following is the *correct* statement ?

(*a*) All the reversible engines have the same efficiency

(*b*) All the reversible and irreversible engines have the same efficiency

(*c*) Irreversible engines have maximum efficiency

(*d*) All engines are designed as reversible in order to obtain maximum efficiency.

ANSWERS

1. (*a*)	2. (*c*)	3. (*c*)	4. (*e*)	5. (*b*)	6. (*b*)	7. (*a*)
8. (*b*)	9. (*d*)	10. (*a*)	11. (*a*)	12. (*a*)	13. (*a*)	14. (*a*)
15. (*a*)	16. (*c*)	17. (*b*)	18. (*c*)	19. (*e*)	20. (*a*)	21. (*d*)
22. (*d*)	23. (*d*)	24. (*a*)	25. (*a*)	26. (*d*)	27. (*a*)	28. (*d*)
29. (*d*)	30. (*a*)	31. (*d*)	32. (*a*)	33. (*c*)	34. (*e*)	35. (*a*)
36. (*d*)	37. (*b*)	38. (*a*)	39. (*e*)	40. (*a*)	41. (*e*)	42. (*d*)
43. (*a*)	44. (*c*)	45. (*b*)	46. (*e*)	47. (*d*)	48. (*b*)	49. (*a*)
50. (*d*)	51. (*a*)	52. (*a*)	53. (*b*)	54. (*e*)	55. (*e*)	56. (*b*)
57. (*b*)	58. (*d*)	59. (*a*)	60. (*c*)	61. (*d*)	62. (*d*)	63. (*b*)
64. (*e*)	65. (*c*)	66. (*a*)	67. (*a*)	68. (*d*)	69. (*e*)	70. (*a*)
71. (*d*)	72. (*d*)	73. (*a*).				

Copyrighted material

For More Visit:www.LearnEngineering.in

THEORETICAL QUESTIONS

1. Define a thermodynamic system. Differentiate between open system, closed system and an isolated system.
2. How does a homogeneous system differ from a heterogeneous system ?
3. What do you mean by a pure substance ?
4. Explain the following terms :
   (*i*) State, (*ii*) Process, and (*iii*) Cycle.
5. Explain briefly zeroth law of thermodynamics.
6. What is a quasi-static process ?
7. What do you mean by 'reversible work' ?
8. Define 'internal energy' and prove that it is a property of a system.
9. Explain the First Law of Thermodynamics as referred to closed systems undergoing a cyclic change.
10. State the First Law of Thermodynamics and prove that for a non-flow process, it leads to the energy equation $Q = \Delta U + W$.
11. What is the mechanical equivalent of heat ? Write down its value when heat is expressed in kJ and work is expressed in N-m.
12. What do you mean by "Perpetual motion machine of first kind-PMM 1" ?
13. Why only in constant pressure non-flow process, the enthalpy change is equal to heat transfer ?
14. Prove that the rate of change of heat interchange per unit change of volume when gas is compressed or expanded is given by $\frac{\gamma - n}{\gamma - 1} \times \frac{pdv}{J}$.
15. Write down the general energy equation for steady flow system and simplify when applied for the following systems :
    (*i*) Centrifugal water pump (*ii*) Reciprocating air compressor
    (*iii*) Steam nozzle (*iv*) Steam turbine
    (*v*) Gas turbine.
16. Explain clearly the difference between a non-flow and a steady flow process.
17. State the limitations of first law of thermodynamics.
18. What is the difference between a heat engine and a reversed heat engine ?
19. Enumerate the conditions which must be fulfilled by a reversible process. Give some examples of ideal reversible processes.
20. What is an irreversible process ? Give some examples of irreversible processes.
21. Give the following statements of second law of thermodynamics.
    (*i*) Clausius statement
    (*ii*) Kelvin-Planck statement.
22. Define heat engine, refrigerator and heat pump.
23. What is the perpetual motion machine of the second kind ?
24. What do you mean by 'Thermodynamic temperature' ?
25. What do you mean by 'Clausius inequality' ?
26. Describe the working of a Carnot cycle.
27. Derive an expression for the efficiency of the reversible heat engine.
28. What do you mean by the term 'Entropy' ?

Copyrighted material

For More Visit:www.LearnEngineering.in