**PES University**
**Department of Mechanical Engineering**
**UE18ME101: Mechanical Engineering Sciences**

**Detailed Lesson Plan**

**Unit-2 : Thermal Energy Systems**

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# 1 Concepts of Thermodynamics and Properties of Gases

## Chapter Objectives

**In this chapter, you will learn about:**

- Basic concepts of thermodynamics
- Internal energy
- First law of thermodynamics and its applications
- Second law of thermodynamics and its significance
- Entropy
- Internal energy
- Relationship between $C_p$ and $C_v$
- Non-flow processes
- Third law of thermodynamics
- Gas laws

## 1.1 INTRODUCTION

There are different forms of energy; all the energy cannot be used as a work. The convertibility of energy into work depends on its availability, i.e., how much energy can be converted into useful work. Thermodynamics is a branch of science and engineering that deals with interaction of energy mainly in the forms of heat and work. Thermodynamics is concerned with thermal behaviour of a matter and its interaction with other physical and chemical behaviour of the matter. Broadly, thermodynamics is studied in two forms—classical and statistical. Classical thermodynamics is concerned with the macrostructure of matter. It addresses the major characteristics of large aggregations of molecules and not the behaviour of individual molecules. The microstructure of matter is studied in kinetic theory and statistical mechanics. Statistical thermodynamics is concerned with the microstructure of the matter and addresses behaviour of individual molecules of the matter. In this chapter, only classical approach to thermodynamics has been discussed. Gases are very important part of engineering thermodynamics; therefore, to know the behaviour of ideal gas at standard temperature and pressure is very important. In this chapter, we have also discussed about the different gas laws and universal gas constants.

## 1.2 IMPORTANT TERMINOLOGIES USED IN THERMODYNAMICS

***Thermodynamics:*** It is the field of thermal engineering that studies the properties of systems that have a temperature and involve the laws that govern the conversion of energy from one form to another, the direction in which heat will flow, and the availability of energy to do work.

***System:*** System is the fixed quantity of matter and/or the region that can be separated from everything else by a well-defined boundary/surface. Thermodynamic system is the system on which thermodynamic investigation is done. The surface separating the system and surroundings is known as the *control surface* or *system boundary*. The control surface may be movable or fixed. Everything beyond the system is the *surroundings*. A system of fixed mass is referred to as a closed system. When there is flow of mass through the control surface, the system is called an *open system*. An *isolated system* is a closed system that does not interact in any way with its surroundings.

***State:*** At any instant of time, the condition of a system is called *state*. The state at a given instant of time is defined by the properties of the system such as pressure, volume, temperature, etc. A *property* is any quantity whose numerical value depends on the state but not on the history of the system. There are two types of properties—extensive and intensive. Extensive properties depend on the size or extent of the system. Volume, mass, energy, and entropy are examples of extensive properties.

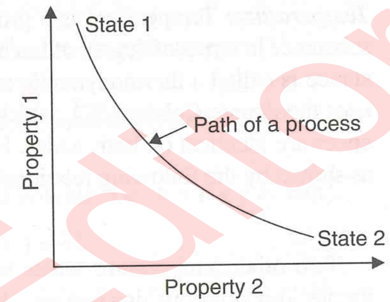

**Figure 1.1** Change in State with a Process

An extensive property is additive in the sense that its value for the whole system equals the sum of the values for its molecules. Intensive properties are independent of the size or extent of the system. Pressure and temperature are examples of intensive properties.

***Change in State:*** Thermodynamic system undergoes changes due to flow of mass and energy. The mode in which the changes in the state of a system takes place is known as process such as isobaric (constant pressure) process, isochoric (constant volume) process, isothermal (constant temperature) process, adiabatic (constant entropy) process, etc. The path is loci of series of state changes from initial state to final state during a process. The change in state and path of a process are shown in Figure 1.1. The thermodynamic cycle refers to sequence of processes in which initial and final states of the system are same. For example, Otto cycle, Diesel cycle, Duel cycle, Joule cycle, Rankine cycle, Carnot cycle, etc. have identical initial and final states.

***Equilibrium:*** In thermodynamics the concept of equilibrium includes not only a balance of forces, but also a balance of other influencing factors, such as thermal equilibrium, pressure equilibrium, phase equilibrium, etc. To observe a thermodynamic equilibrium in a system, one may test it by isolation of the system from its surroundings and watch for changes in its observable properties. If no change takes place, it may be said that the system is in equilibrium. The system can be at an equilibrium state. When a system is isolated, it cannot interact with its surroundings; however, its state can change as a consequence of spontaneous changes occurring internally as its intensive properties, such as temperature and pressure, tend toward uniform values. When all such changes cease, the system is in equilibrium. At equilibrium, temperature and pressure are uniform throughout. If gravity is significant, a pressure variation with height can exist, as in a vertical column of liquid.

*Zeroth law of thermodynamics is law of thermal equilibrium, which states that if a system A is in thermal equilibrium with systems B and C, then systems 3 and C will be in thermal equilibrium as well.*

***Work:*** Work in thermodynamics may be defined as any quantity of energy that flows across the boundary between the system and surroundings which can be used to change the height of a mass in the surroundings.

***Heat:*** Heat is defined as the quantity of energy that flows across the boundary between the system and surroundings because of a temperature difference between system and surroundings. The characteristics of heat are as follows:

- Heat is transitory and appears during a change in state of the system and surroundings. It is not a point function.
- The net effect of heat is to change the internal energy of the system and surroundings in accordance to first law.
- If heat is transferred to the system, it is positive and if it is transferred from the system it is negative.

## 1.4 THE FIRST LAW OF THERMODYNAMICS

### 1.4.1 Mechanical Equivalent of Heat

The *mechanical equivalent of heat* is a concept that has an important part in the development and acceptance of the conservation of energy and the establishment of the science of thermodynamics in the 19th century. The concept stated that motion and heat are mutually interchangeable and that in every case, a given amount of work would generate the same amount of heat, provided the work done is totally converted to heat energy.

**First Law of Thermodynamics**

The first law of thermodynamics is equivalent to law of conservation of energy. It deals with the transformation of heat energy into work and vice versa. For closed systems, energy can be transferred by work and heat transfer. In thermodynamics, the term *work* denotes a means for transferring energy. Work done by a system is considered positive: $W > 0$. Work done on a system is considered negative: $W < 0$. Heat given to a system is considered as positive: $Q > 0$. Heat exhaust by a system is considered as negative: $Q < 0$. The heat generation by the work done on the system is shown in Figure 1.2.

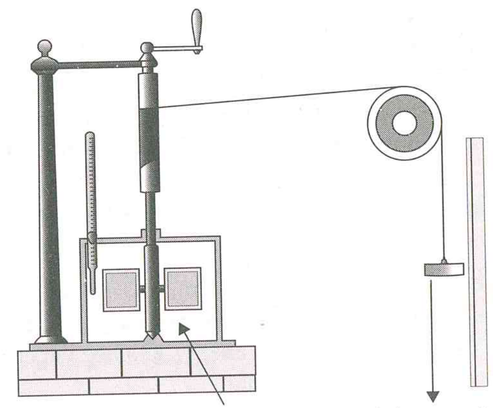

Figure 1.2 Mechanical Equivalent of Heat

*When a small amount of work (dw) is supplied to a closed system undergoing a cycle, the work supplied will be equal to the heat transfer or heat produced (dQ) in the system.*

$$\oint dw = J \oint dQ$$

where $J$ is a joule constant; 1 cal = 4.18 J.

*If Q amount of heat is given to a system undergoing a change of state and W is work done by the system and transferred during the process, the net energy (Q – W) will be stored in the system named as internal energy or simply energy of the system (ΔU).*

$$Q - W = \Delta U$$

### 1.4.4 Energy Transfer Across the System Boundary (Heat and Work)

Energy transfer across the boundary of a closed system may occur in the form of heat and work. When a closed system is left in a medium of different temperature, energy transfer takes place between the system and the surrounding until thermal equilibrium is reached. The direction of energy transfer is always from the higher temperature side to the lower temperature side. Once the temperature equilibrium is established, energy transfer stops. In the processes described earlier, energy is said to be transferred in the form of heat. Heat is defined as the form of energy that is transferred between two systems or between a system and its surroundings by virtue of a temperature difference.

During adiabatic process heat transfer is negligible. A process can be adiabatic when either the system is well insulated so that only a negligible amount of heat can pass through the boundary or both the system and the surroundings are at the same temperature. Even though there is no heat transfer during an adiabatic process, the energy content, and thus the temperature of a system can still be changed by other means such as work, i.e., the heat can be transformed into work. If the energy crossing the boundary of a closed system is not heat, it must be work. Heat is easy to recognize as its driving force is a temperature difference between the system and its surroundings. Then we can simply say that an energy interaction that is not caused by a temperature difference between a system and its surroundings is work.

#### Sign Conventions for Heat and Work Interaction

Heat and work are directional quantities, and thus the complete description of a heat or work interaction requires the specification of both the magnitude and direction. One way of doing that is to adopt a sign convention. The generally accepted formal sign convention for heat and work interactions is as follows:

- Heat transfer to a system and work done by a system are positive.
- Heat transfer from a system and work done on a system are negative.

#### Similarity Between Heat and Work

Heat and work are energy transfer mechanisms between a system and its surroundings. Some of the similarities between heat and work are as follows:

- Heat and work are boundary phenomena.
- Systems possess energy, but not heat or work.
- Both are associated with a process, not a state.
- Both are path functions.

**Example 1.3:** A system undergoes the cyclic process abcde. The values of $Q$, $W$, and $\Delta u$ for the individual process are as follows:

| Process | $Q$ (kJ) | $\Delta u$ (kJ) | $W$ (kJ) |
|---|---|---|---|
| a–b | – | –510 | 310 |
| b–c | 410 | – | –510 |
| c–d | 510 | 610 | – |
| d–e | – | – | 810 |

**Solution:**

Process $a-b$: $Q = \Delta u + W = -510 + 310 = -200\,\text{kJ}$ (Heat liberated).

Process $b-c$: $Q = \Delta u + W \Rightarrow 410 = \Delta u - 510$ or $\Delta u = 920\,\text{kJ}$

Process $c-d$: $Q = \Delta u + W \Rightarrow W = Q - \Delta u = 510 - 610 = -100\,\text{kJ}$ (Work done on system)

In a cyclic process $\int \Delta u = 0 \Rightarrow \Delta u_{ab} + \Delta u_{bc} + \Delta u_{cd} + \Delta u_{de}$

$$-510 + 920 + 610 + \Delta u_{de} = 0 \Rightarrow \Delta u_{de} = -1{,}020\,\text{kJ}$$

$$Q = \Delta u + W = -1{,}020 + 810 = -210\,\text{kJ (Heat liberated)}$$

... system in which pressure is a function of volume as $P = x + yV$

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### 1.4.7 Limitations of First Law of Thermodynamics

First law of thermodynamics does not tell about the following:

- How much of the given quantity of heat is changed into work?
- In which direction is changing take place (heat to work or work to heat)?
- Under which condition the changing will take place?

## 1.5 THE SECOND LAW OF THERMODYNAMICS

Second law of thermodynamics overcomes the limitations of first law of thermodynamics. First law of thermodynamics does not tell how much of heat is changed into work. Second law of thermodynamics shows that the total heat supplied to a system cannot be transferred solely into the work using single reservoir, i.e., some part of heat must be rejected to sink. It also shows the direction of the energy transfer, i.e., heat cannot be transferred from lower temperature reservoir to higher temperature reservoir without external work done on the system.

### 1.5.1 Kelvin–Planck Statement

The Kelvin–Plank statement of the second law of thermodynamics refers to a thermal reservoir. A thermal reservoir is a system of infinite heat capacity that remains at a constant temperature even though energy is added or removed by heat transfer. A reservoir is an idealization, of course, but such a system can be approximated in a number of ways—by the Earth's atmosphere, large bodies of water (oceans), and so on.

The Kelvin–Planck statement of the second law can be given as: *It is impossible for any system to operate in a thermodynamic cycle and deliver a net amount of energy by work to its surroundings while receiving energy by heat transfer from a single thermal reservoir.*

In Figure 1.11, it is shown that there are two reservoirs from which heat is interacted to do a work $W_{net}$. Heat, $Q_H$ is taken from higher temperature reservoir and work is done and rest amount of heat is rejected to lower temperature reservoir. Thus, the total conversion of heat to work is impossible; there will always be rejection of some part of the heat supplied by the heat engine.

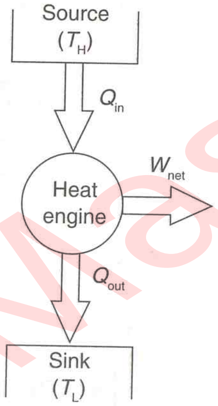


Figure 1.11 Heat Engine

### 1.5.2 Clausius Statement

*It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower temperature body to higher temperature body.* In other words, a refrigerator cannot be operated without external work supplied to refrigeration system.

s
t

## 1.6 Heat Engine:

In thermodynamics, a heat engine is a system that converts heat or thermal energy—and chemical energy—to mechanical energy, which can then be used to do mechanical work.
It does this by bringing a working substance from a higher state temperature to a lower state temperature
Refer Fig 1.11

## FILL IN THE BLANKS

1. The system and surrounding together constitute ___________ system.
2. In an adiabatic process, energy can be exchanged in the form of ___________.
3. For an ideal gas ($dh/dT$) is a measure of ___________ at constant pressure.
4. Second law of thermodynamics establishes the law of ___________.
5. The slope of constant volume line on $T$–$S$ diagram is ___________ than that of constant pressure line.
6. The unit of entropy is ___________.
7. In case of free expansion enthalpy ___________.
8. The entropy of universe tends to be ___________.

### Answers

1. Isolated, 2. Heat, 3. Specific heat, 4. Entropy, 5. More, 6. kJ/kg K, 7. Remains constant, 8. Maximum.

## REVIEW QUESTIONS

1. What is prime mover? Discuss its importance in energy conversion.
2. Explain the various sources of energy mentioning renewable and non-renewable sources.
3. What do you mean by non-conventional energy sources? How does it differ from conventional sources?
4. Explain the scope of solar energy and its future applications.
5. Define: (i) property, (ii) state, (iii) system, (iv) control volume, and (v) process.
6. Discuss the concept of thermal equilibrium and state zeroth law of thermodynamics.
7. What do you understand by quasi-static process? How it is achieved?
8. Differentiate among temperature, heat, and internal energy.
9. Derive an expression for first law of thermodynamics applied to a closed system. Define the internal energy of a system.
10. Define work. Show that work done $W = PdV$.
11. Discuss the thermodynamics system, surrounding, and universe. Also discuss the various types of system with suitable example.
12. Prove that work and heat are the path function.
13. Derive the expression for work done in steady flow process.
14. Distinguish between the term 'change of state', 'path', and 'process'.
15. State the zeroth law of thermodynamics and first law of thermodynamics.
16. Explain and derive steady flow energy equation (SFEE).
17. State the Kelvin–Planck and Clausius statements of second law of thermodynamics. Explain the equivalence of Kelvin–Planck and Clausius statements.
18. State and explain Carnot theorem.
19. Write the statement of Boyle's law.
20. Write the statement of Charle's law.
21. Write the statement of Gay–Lussac's law.
22. Derive the expression for combined gas law.
23. Explain the term gas constants.

## PROBLEMS FOR PRACTICE

1. An ideal gas is heated from 25°C to 145°C. The mass of the gas is 2 kg. Determine (i) specific heats, (ii) change in internal energy, and (iii) change in enthalpy. Assume $R = 267$ J/kg K and $\gamma = 1.4$ for the gas.
2. A single stage compressor is required to compress 94 m$^3$ air per min from 1 bar and 25°C to 9 bar. Find the temperature at the end of compression, work done, power required and heat rejected during each of the following process: (i) isothermal, (ii) adiabatic, and (iii) polytropic following the law $PV^{1.3} =$ constant. Assume no clearance.
3. Determine the work done in compressing 1 kg of air from a volume of 0.15 m$^3$ at a pressure of 1 bar to a volume of 0.05 m$^3$, when the compression is (i) isothermal, and (ii) adiabatic, take $\gamma = 1.4$.
4. 0.15 m$^3$ of air at pressure of 900 kPa and 300°C is expanded at constant pressure to three times its initial volume. It is expanded polytropically following the law $PV^{1.5} = C$ and finally compressed back to initial state isothermally. Calculate heat received, heat rejected, and efficiency of cycle.
5. In air compressor air enters at 1.013 bar and 27°C having volume 5 m$^3$/kg and it is compressed to 12 bar isothermally. Determine work done, heat transfer, and change in internal energy.
6. The work and heat per degree change of temperature for a process executing a non-flow process is given by $\dfrac{\delta W}{\delta T} = 160\ \mathrm{W}/{}^\circ\mathrm{C}$ and $\dfrac{\delta Q}{\delta T} = 200\ \mathrm{J}/{}^\circ\mathrm{C}$. Determine change in internal energy of a system when its temperature increases from 60°C to 110°C.
7. A blower handles 2 kg/s of air at 30°C and consumes 40 kW power. The inlet and outlet velocities of air are 100 and 150 m/s, respectively. Find exit temperature assuming process is adiabatic (take $C_p$ for air 1.005 kJ/kg K).
8. The centrifugal pump delivers 50 kg of water per second. The inlet and outlet pressures are 1 and 4.2 bar, respectively. The suction is 2.2 m below the centre of the pump and delivery is 8.5 m above the centre of the pump. The suction and delivery pipe diameters are 20 and 10 cm, respectively. Determine the capacity of the electric motor to run the pump.
9. Two reversible heat engines $E_1$ and $E_2$ are arranged in series between a hot reservoir at temperature $T_1$ of 600 K and a cold reservoir at temperature $T_2$ of 300 K. Engine $E_1$ receives 500 kJ of heat from reservoir at $T_1$. Presuming both engine has equal thermal efficiency, determine the temperature at which heat is rejected by $E_1$ and received by $E_2$, thermal efficiency of each engine, work done by engine $E_1$ and $E_2$ and heat rejected by $E_2$ to cold reservoir.
10. A reversible heat engine operates between 875 and 310 K and drives a reversible refrigerator operating between 310 and 255 K. The engine receives 2,000 kJ of heat and net work output from the arrangement equals 350 kJ. Make calculations for cooling effect.
11. A new temperature scale in degree N is desired with freezing point at 100°N and the boiling point at 400°N. Establish a correlation between degrees Celsius and degrees N. What would be the absolute temperature at 0°N?
12. A reversible heat engine operates within the higher and lower temperature limits of 1,400 and 400 K, respectively. The entire output from this engine is utilized to operate a heat pump. The pump works on reversed Carnot cycle, extracts heat from a reservoir at 300 K and delivers it to the reservoir at 400 K. If 100 kJ/s of net heat is supplied to the reservoir at 400 K, calculate the heat supplied to the engine by reservoir at 1,400 K.

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# Internal Combustion Engines

## Chapter Objectives

**In this chapter, you will learn about:**

- IC engine and its classification
- Classification of IC engines
- Constructional details and working of SI and CI engines
- Two-stroke and four-stroke engines
- Valve timing diagrams
- Thermodynamic cycles: Otto, diesel and dual cycles
- Testing and performance of IC engines

## 6.1 INTRODUCTION

"The heat engine, in which the combustion takes place inside the cylinder or the product of combustion (flue gas) directly goes to the cylinder and the heat energy of the flue gas is converted into mechanical energy, is known as Internal Combustion Engine (IC Engine)." The combustion may take place either inside or outside the cylinder, but heat energy of the combustion is directly utilized by the engine to produce into mechanical power. However, in external combustion engines, heat of the combustion is transferred to the intermediate medium like water or air and then the heat energy of that intermediate medium (steam produced from the water or the hot air) is converted into the mechanical energy. The steam engine/turbine and closed cycle gas turbine work on the principle of external combustion engine as the heat of combustion is transferred to water and air, respectively. The steam produced from water in case of steam engine/turbine and hot compressed air in case of closed cycle gas turbine produce mechanical power. While automobile and open cycle gas turbine work on the principle of internal combustion engine as the flue gas produced during combustion produces mechanical power without transferring the heat energy to any intermediate medium.

## 6.2 CLASSIFICATION OF IC ENGINES

There are several bases for classification of IC engines, some of the important bases can be explained as

- Number of strokes per cycle.
- Nature of thermodynamic cycle.
- Ignition systems.
- Fuel used.
- Arrangement of cylinders.
- Cooling systems.
- Fuel supply systems.

***Number of Strokes per Cycle:*** IC engines can be classified as four stroke engines (4S) and two stroke engines (2s). In four stroke engines, the thermodynamic cycle is completed in four strokes of the piston or two revolutions of the crankshaft whereas in two stroke engines, the thermodynamic cycle is completed in two strokes of the piston or one revolution of the crankshaft.

***Nature of Thermodynamic Cycle:*** IC engines can be classified as Otto cycle, diesel cycle, and dual cycle engine. In Otto cycle engine, heat addition, and heat rejection occur at constant volume; therefore, this is also known as constant volume engine whereas in diesel cycle engine, heat addition occurs at constant pressure, and heat rejection occurs at constant volume. In dual cycle, heat addition occurs partly at constant volume and partly at constant pressure but heat rejection occurs fully at constant volume.

***Ignition Systems:*** There are two modes of ignition of fuel inside the cylinder: spark ignition and self or compressed ignition. In spark ignition, sparking starts at the end of compression stroke from spark plug while in compressed ignition the temperature of the fuel is increased to the self-ignition point by compressing the air alone and at the end of compression fuel is injected inside the cylinder.

***Fuel Used:*** On the basis of fuel used, IC engines can be classified as:

- Gas engines like CNG, natural gas, etc.
- Petrol engine.
- Diesel engine.
- Bi-fuel engine.

In bi-fuel engine two types of fuel are used like gaseous fuel and liquid fuel.

***Arrangement of Cylinders:*** According to arrangement of cylinders (Figure 6.1), IC engines can be classified as:

- In-line engines.
- V-engines.
- Opposed cylinder engines.
- Opposed piston engines.
- X-type engines.
- Radial engines.

In an in-line cylinder engine, all the cylinders are arranged linearly and transmit power through a single crankshaft. V-engines have two banks of cylinders arranged in the shape of English letter V and single crankcase and crankshaft is used to transmit the power. In opposed cylinder engines, all

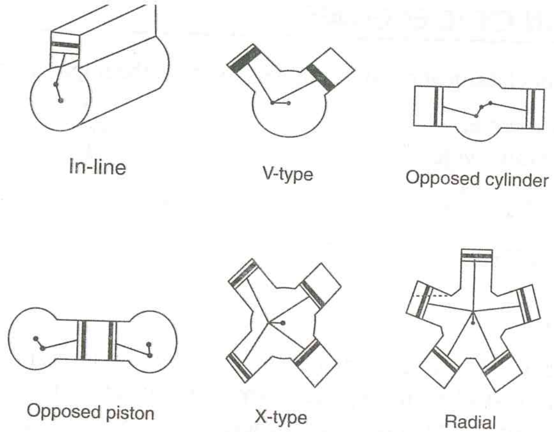


Figure 6.1 Classification of IC Engines on the Basis of Cylinders Arrangement

the cylinders lie in same plane but the cylinders are arranged on both sides of the crankshaft at 180°. It is inherently well balanced. When a single cylinder houses two pistons each of which drives a separate crankshaft, it is called an opposed piston engine. The moments of the pistons are synchronized by coupling two crankshafts. It is also inherently well balanced. X-type engines have four cylinders with single crankcase and single crankshaft. The cylinders are arranged in the shape of English letter X. In radial engine, cylinders are arranged in radial directions like the spokes of a wheel and are connected to a single crankshaft. These engines are used in conventional air-cooled aircraft engines.

***Cooling Systems:*** There are two types of cooling systems in IC engines: water cooling and air cooling. In water cooling, coolant, and radiators are provided to cool the cylinder. In air cooling, fins are provided on the surface of the cylinder to radiate the heat into the atmosphere. Low power engines like motorbikes are equipped with air cooling systems whereas large power producing engines like car, bus, truck, etc. are equipped with water cooling systems.

***Fuel Supply Systems:*** On the basis of fuel supply systems, IC engines can be classified as:

- Carburettor engine.
- Air injection engine.
- Airless or solid or mechanical injection engines.

In a carburettor engine, air, and fuel are properly mixed into the carburettor and then fed into the cylinder. In air injection engines, fuel is supplied to the cylinder with the help of compressed air. In mechanical injection engines, the fuel is injected inside the cylinder with the help of mechanical pump and nozzle.

## 6.3 BASIC STRUCTURE OF IC ENGINES

Even though reciprocating internal combustion engines look very simple in appearance, they are highly complex machines. There are a large number of components which have to perform their functions to produce power. Before going through the working principle of the complex machine, a brief description of the engine components is shown in Figure 6.2.

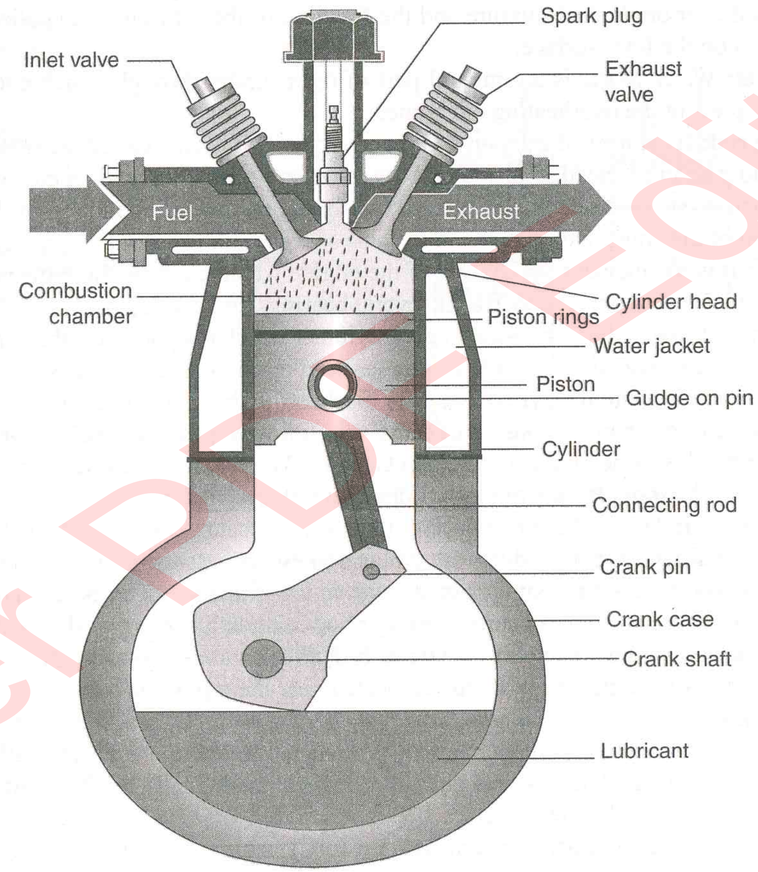


Figure 6.2 The Components of an IC Engine

- **Cylinder:** It is a hollow cylindrical structure closed at one end with cylinder head. The combustion of the fuel takes place inside the cylinder. This is known as heart of the engine. It is made of hard and high thermal conductivity materials by casting. A piston reciprocates inside the cylinder and produces power.
- **Cylinder head:** It covers one end of the cylinder and consists of valves/ports and spark plug/injector.
- **Cylinder liner:** The internal surface of the cinder is equipped with replaceable liner which can be easily replaced after wear and tear. Liner is used to protect the wear of the cylinder so that replacement of complete cylinder can be avoided.
- **Piston:** It is a cylindrical component which is fitted perfectly inside the cylinder providing a gas tight space with the piston rings and the lubricant. The piston is connected to connecting rod by hardened gudgeon pin. The main function of the piston is to transfer the power produced by combustion of the fuel to the crankshaft.
- **Piston rings:** The outer periphery of the piston is provided with several grooves into which piston rings are fitted. The piston is fitted with these rings. The upper ring is known as compression ring and the lower rings are known as oil rings. The function of the compression ring is

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to compress the air or air–fuel mixture and the function of the oil rings is to collect the surplus lubricating oil on the liner surface.

- **Water jacket:** Water jacket is an integral part of the cylinder through which cooling water is circulated to prevent the overheating of engine.
- **Connecting rod:** It connects the piston and the crankshaft. One end, called the small end, is connected to gudgeon pin located in piston and the other end, called big end, is connected to crank pin. The function of the connecting rod is to transfer the reciprocating motion of the piston into rotary motion of the crankshaft.
- **Crankshaft:** It is a principal rotating part of the engine which controls the sequence of reciprocating motion of the pistons. It consists of several bearings and crank pins.
- **Valves:** Normally, two valves are used for each cylinder which may be of mushroom shaped poppet type. They are provided either on the cylinder head or on the side of the cylinder for regulating the charge coming into the cylinder and for discharging the products of combustion from the cylinder. The valve mechanism consists of cams, cam follower, push rod, rocker arms, and spring.
- **Inlet manifold:** This is the pipe which connects the intake system to the inlet valve of the engine and through which air or air–fuel mixture is drawn into the cylinder.
- **Exhaust manifold:** This is the pipe which connects the exhaust system to the exhaust valve of the engine and through which products of combustion escape into the atmosphere.
- **Cams and camshaft:** Cam is mounted on a shaft which is known as camshaft. The function of the cam is to facilitate the control of the timing of opening and closing of the inlet and exhaust valve. It provides to and fro motion to the valve rods to open and close the valves.
- **Spark plug:** In a S.I. engine, a spark plug is located near the top of the cylinder and initiates the combustion of the fuel.
- **Carburettor:** Carburettor is a device which is used to control the fuel qualitatively in a S.I engine. It atomizes the fuel, mixes with air and vaporizes it and finally sends the air–fuel mixture inside the cylinder through inlet valve.
- **Fuel pump and injector unit:** This unit is used in CI engines (nowadays injection system is also used in S.I engine as multi-point fuel injection, MPFI). Its function is to supply the fuel to injector under pressure which consists of one or more orifices through which the fuel is sprayed into the cylinder.
- **Crank case:** It consists of cylinder, piston, and crankshaft. It helps in lubrication of different parts of the engine.
- **Flywheel:** It is a heavy wheel mounted on the crankshaft to minimize the cyclic variations in speed. It absorbs the energy during power stroke and releases it during non-power stroke. By employing a flywheel, the turning moment becomes uniform at crankshaft.

### 6.3.1 Nomenclature

There are various terms which are frequently used in an IC engine and are discussed below.

- **Cylinder bore (d):** The nominal inner diameter of a cylinder is called cylinder bore which is designated by an English letter 'd' and expressed in millimetre (mm).
- **Piston area (A):** The area of the inner diameter of a cylinder is known as piston area. It is measured in terms of square centimetre ($cm^2$) or square millimetre ($mm^2$).
- **Stroke (L):** The axial distance for which a piston moves inside a cylinder in one stroke is known as stroke or stroke length (Figure 6.3) which is designated by an English letter 'L' and measured in terms of millimetre (mm).

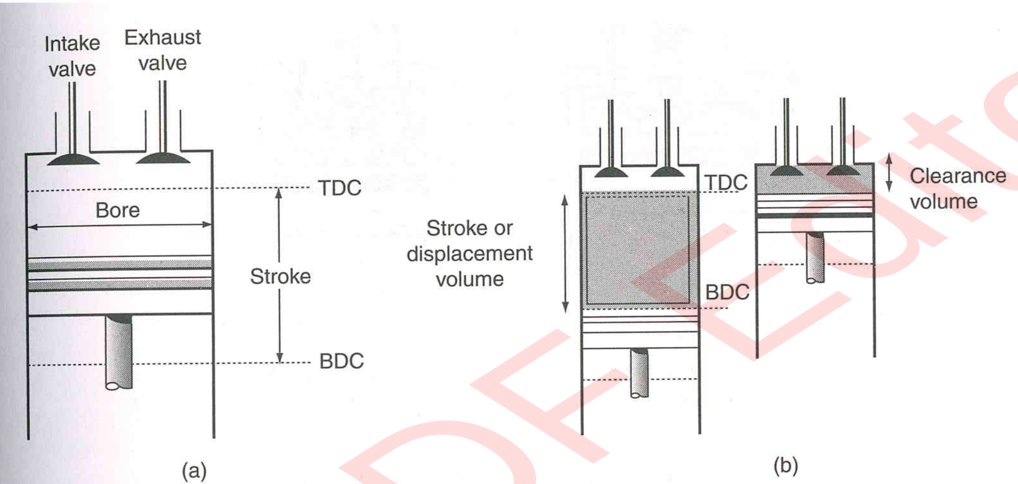



Figure 6.3 Stroke Length and Stroke Volume in an IC Engine

- **Dead centres:** The positions of the piston, at the moments when the direction of the piston motion is reversed are known as dead centres. There are two dead centres—top dead centre (TDC) and bottom dead centre (BDC). The farthest position of the piston head from the crankshaft is known as TDC and nearest position of the piston head from the crankshaft is known as BDC as shown in Figure 6.3.
- **Displacement/stroke/swept volume ($V_s$):** The nominal volume swept by the working piston when travelling from one dead centre to the other is called the displacement volume. It is expressed in terms of cubic centimetre (cc) and is given by,

$$V_s = A \times L = \frac{\pi}{4} d^2 L$$

- **Clearance volume ($V_c$):** The nominal volume of the combustion chamber above the piston when it is at the TDC is known as clearance volume ($V_c$) and is expressed in cc.
- **Compression ratio ($r_v$):** It is the ratio of the total cylinder volume when the piston is at BDC to the clearance volume.

$$r_v = \frac{V_c + V_s}{V_c} = 1 + \frac{V_s}{V_c}$$

## 6.4 WORKING PRINCIPLE OF IC ENGINES

Working principle of an IC engine consists of thermodynamic cycle involved to generate the power and thermodynamic processes such as suction, compression, heat addition expansion and heat rejection. In this chapter, we will study the operating principles of four strokes and two strokes of spark ignition engine and compression ignition engine.

### 6.4.1 Four-stroke Spark Ignition Engine

The working of all the four strokes of a spark ignition engine is shown in Figure 6.4. In this engine, the cycle of operations is completed in four strokes of the piston or two revolutions of the crankshaft.

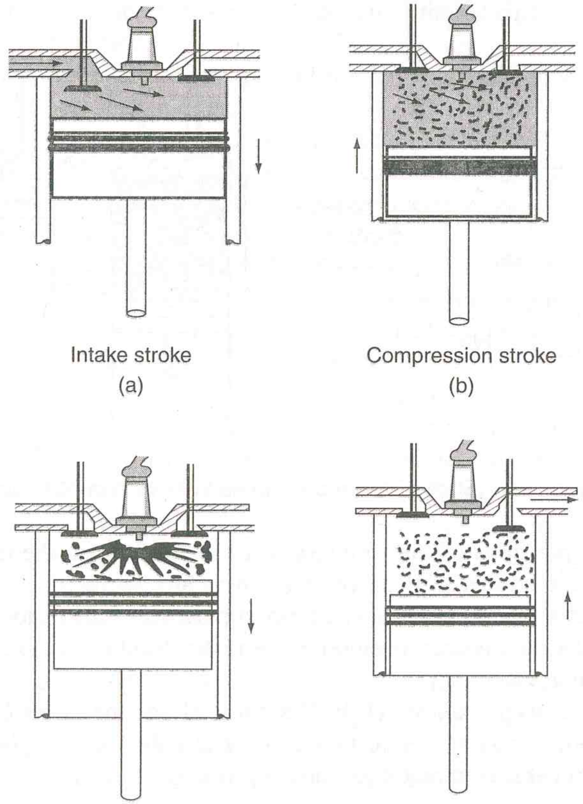



**Figure 6.4** All the Four Thermodynamic Processes in Four Strokes SI Engine

During the four strokes, there are five processes to be completed, viz., suction, compression, combustion, expansion and exhaust. Each stroke consists of 180° rotation of crankshaft and hence a four strokes cycle is completed in two revolutions of crankshaft. The pressure–volume diagram ($P$–$V$ diagram) diagram is shown in Figure 6.5.

***Suction Stroke (0 – 1):*** It starts when piston is at TDC and about to move downward, inlet valve is open and exhaust valve is closed as shown in Figure 6.4a. Due to suction created by the piston movement towards BDC, air–fuel mixture enters into the cylinder. Suction ends when piston reaches at BDC.

***Compression Stroke (1–2):*** At the end of suction stroke, inlet valve is closed and piston moves towards TDC. In this stroke, both valves inlet and exhaust are closed; compression of the air–fuel mixture filled in the cylinder starts from BDC and ends at TDC as shown in Figure 6.4b. At the end of compression and at constant volume (2–3), sparking starts at spark plug and instantaneously burning takes place in the compressed air–fuel mixture. Pressure and temperature are increased to maximum limit.

***Power Stroke (3–4):*** The high pressure developed due to combustion of fuel forces the piston towards BDC. The power is transferred to the crankshaft. Pressure and temperature decrease during the stroke. In this stroke, both the valves are closed as shown in Figure 6.4c.

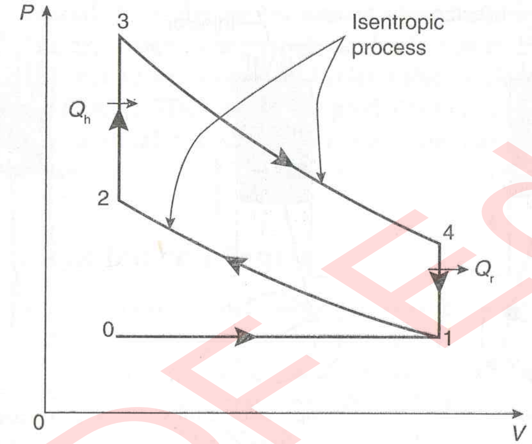



**Figure 6.5** $P$–$V$ Diagram for Otto Cycle

***Exhaust Stroke (4–1):*** At the end of expansion or power stroke, the exhaust valve opens and the inlet valve remains closed as shown in Figure 6.4d. Piston moves towards TDC and exhaust gas is forced to escape into atmosphere through exhaust valve.

### 6.4.2 Four-stroke Compression Ignition Engine

The four stroke compression ignition (CI) engine is very similar to the four-stroke spark ignition engine as shown in Figure 6.6, but it operates at a much higher compression ratio. The compression ratio of SI engines varies from 6 to 10 whereas in CI engines it ranges from 16 to 20. During the suction stroke, air is sucked alone inside the cylinder and then compressed sufficiently to increase the temperature equal to the self-ignition temperature of the fuel injected at the end of compression at constant pressure. In this engine, a fuel pump and injector are used to inject the fuel at high pressure. The ignition system of CI engine is completely different from SI engine as no spark plug and carburettor are required.

The sequence of operations of CI engine can be explained as follows:

- **Suction stroke:** In this stroke, piston moves from TDC to BDC and air is sucked alone as vacuum is created inside the cylinder by the piston movement. During suction inlet valve is open and exhaust valve remains closed as shown in Figure 6.6a. On ideal $P$–$V$ diagram suction is shown by a straight line from 0 to 1 in Figure 6.7.
- **Compression stroke:** Both the valves are closed during the stroke and air is compressed into the clearance volume by the piston movement from BDC to TDC as shown in Figure 6.6b. On $P$–$V$ diagram it is shown by the process 1–2 in Figure 6.7. At the end of compression at constant pressure fuel is injected as shown in Figure 6.6c. Due to high pressure and temperature, fuel starts to ignite automatically as temperature of air is increased to flash point of the fuel. The heat addition process is shown by the line 2–3 on $P$–$V$ diagram.
- **Expansion or power stroke:** Fuel injection starts nearly at the end of the compression stroke. The rate of injection is such that the combustion maintains the pressure constant in spite of the piston movement on its expansion stroke increasing the volume. Heat is assumed to have been added at constant pressure. After the injection of the fuel is completed (after cut-off) the

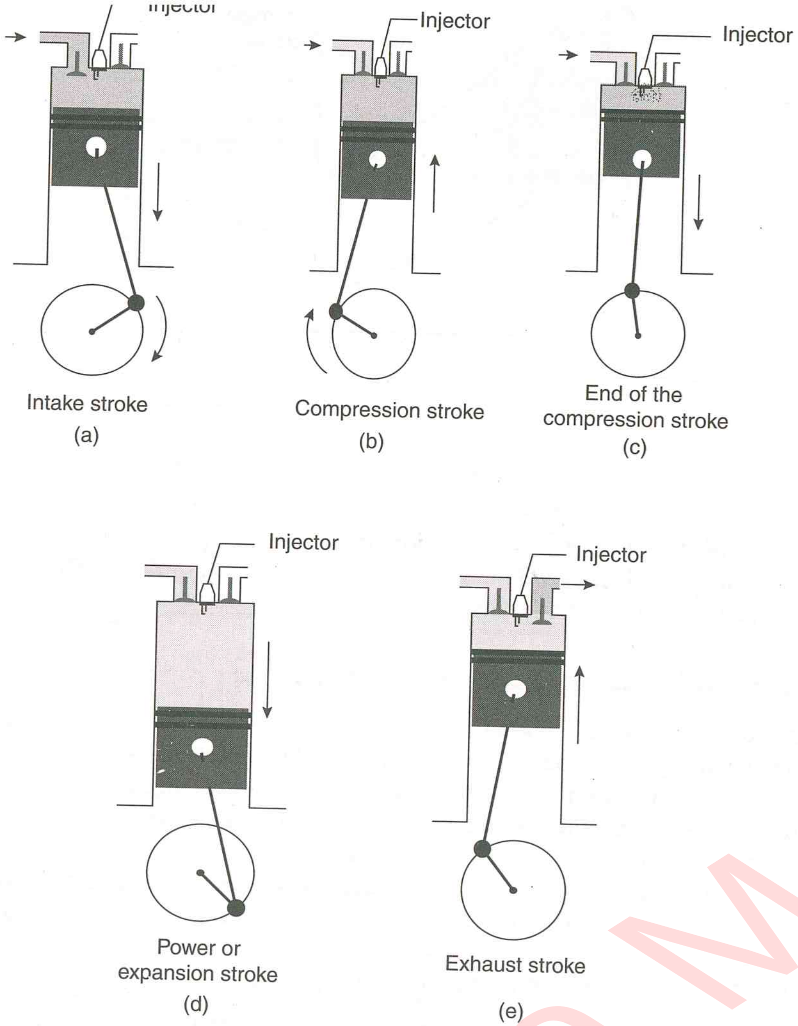



**Figure 6.6** All the Thermodynamic Processes in Four Strokes CI Engine

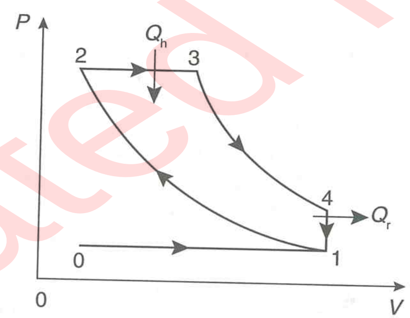



**Figure 6.7** *P–V* Diagram for Diesel Cycle

combustion products expand. Both the valves remain closed during the expansion stroke as shown in Figure 6.6d. The expansion process is shown by 3–4 on *P–V* diagram.

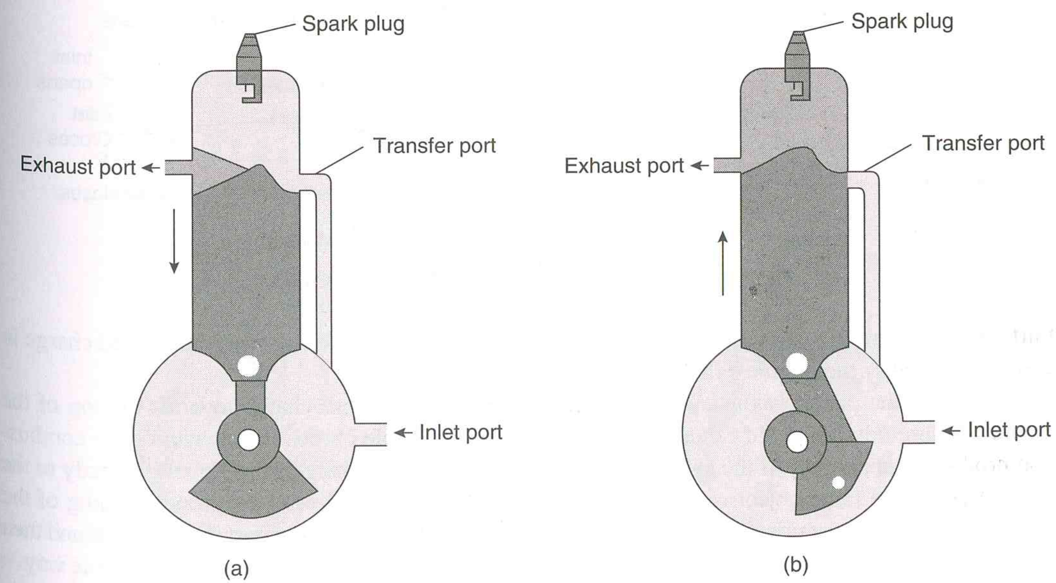
- **Exhaust stroke:** The exhaust valve is open and inlet valve is closed during the stroke. The movement of piston from BDC to TDC pushes the product of combustion and disposed into the atmosphere through the exhaust valve as shown in Figure 6.6e. The exhaust process is shown by the line 4–5 on *P–V* diagram.

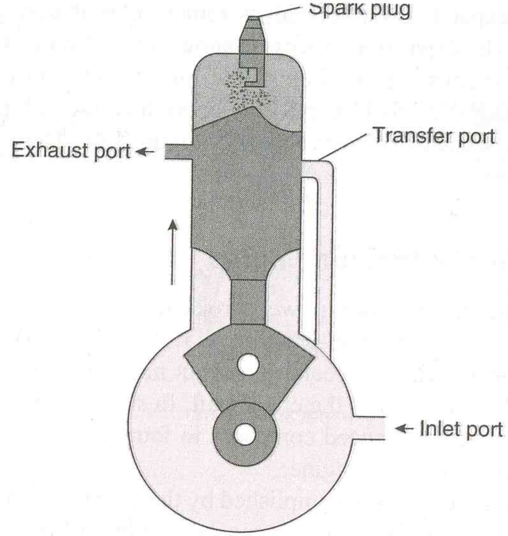
### 6.4.3 Two-stroke Spark Ignition Engine

In a four stroke SI engine, there is one power stroke in two revolutions of crankshaft and two strokes, viz., suction and exhausts are non-productive. If these two non-productive strokes could be served by an alternative arrangement especially without movement of the piston then there will be one power stroke for each revolution of the crankshaft. In such an engine, the power output can be doubled, theoretically, for the same speed compared to four stroke engine. Based on this concept, D. Clark (1878) developed two-stroke engine.

In this engine, the filling process is accomplished by the charge compression in crankcase or by a blower. The induction of the compressed charge pushes the burnt fuel products through the exhaust port. Therefore, no piston movement is required for suction and exhaust process. Two strokes are sufficient to complete the cycle, one for compressing the fresh charge and other for expansion or power stroke. Figure 6.8 shows the simplest form of crankcase scavenged engine. The ideal and actual indicator diagram is shown in Figure 6.9.

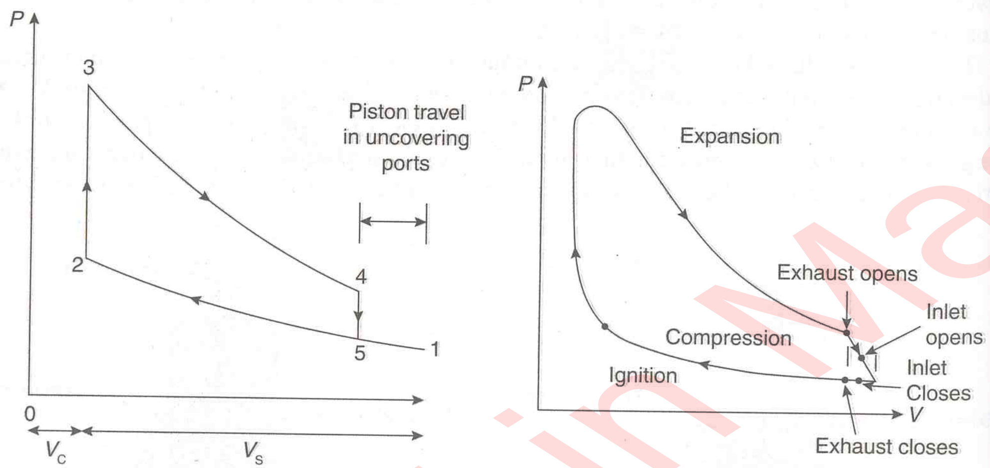
The charge is inducted into the crankcase through the spring loaded inlet valve when the pressure in the crankcase is reduced due to upward movement of the piston during compression stroke. After the compression and ignition, expansion takes place in the usual way. During expansion stroke the charge in crankcase is compressed. Near the end of expansion stroke piston uncovers the exhaust port and cylinder pressure drops to atmospheric pressure as combustion products leaves the cylinder.






(c)

**Figure 6.8** Working of Two Stroke SI Engine




(a) Ideal

(b) Actual

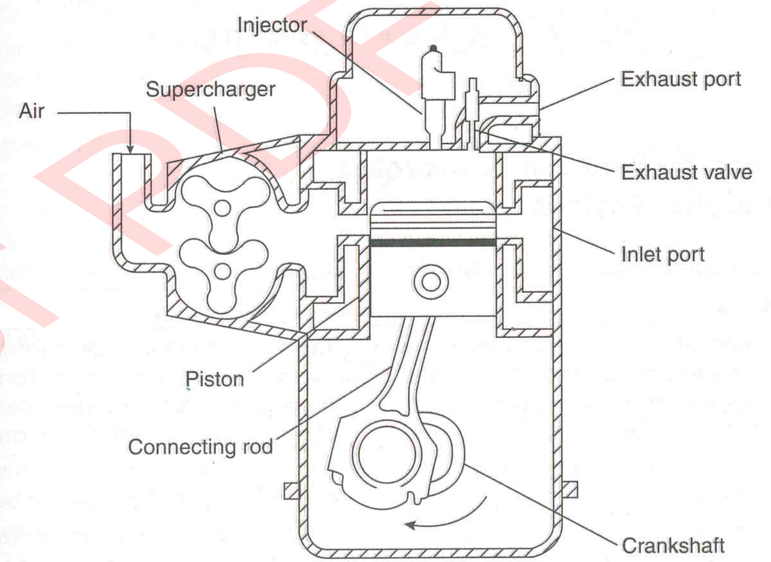
**Figure 6.9** *P–V* Diagrams for Two Strokes SI Engine

Further movement of piston uncovers the transfer port, permitting the slightly compressed charge in crankcase to enter the engine cylinder.

The top of the piston has usually a projection to deflect the fresh charge towards the top of the cylinder before flowing to the exhaust port. This serves the double purpose—scavenging the combustion product in upper part of the cylinder and preventing the fresh charge from flowing directly to the exhaust port. The same objective can be achieved without piston deflector by proper shaping of the transfer port. During the upward motion of the piston from BDC, the transfer port is closed first and then the exhaust port is closed when compression of charge begins and cycle is repeated in the same way.

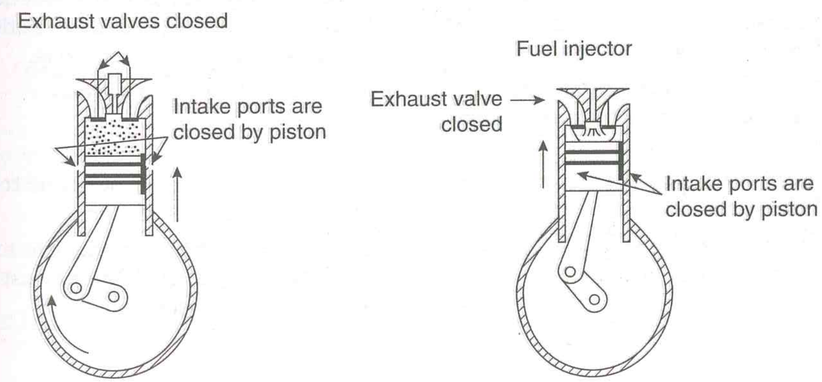
### 6.4.4 Two-stroke CI Engine

The working of two strokes CI engine is very similar to two stroke SI engine. The main difference is that in CI engine supercharged air is used through the inlet port and in place of exhaust ports exhaust valves are used. Pressurized air is inducted through the inlet port which expels the combustion gases through exhaust valve during the expansion stroke. Inlet and exhaust valve is closed during the compression stroke, piston moves from BDC to TDC. At the end of compression fuel is injected inside the cylinder and ignites and piston is forced to move from TDC to BDC. The same process is repeated again and again. The cut model of two stroke CI engine is shown in Figure 6.10 and the working strokes are shown in Figure 6.11.




Two-stroke deisel engine

**Figure 6.10** Cut-section of Two Strokes CI Engine




(a) Compression

(b) Injection

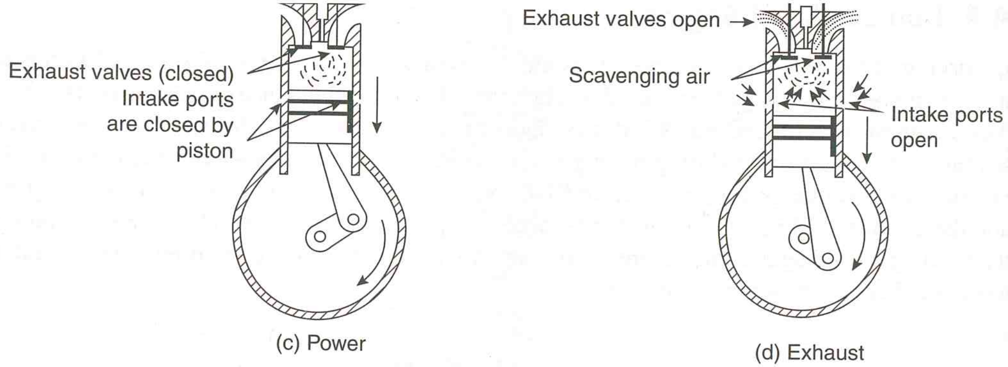



Figure 6.11 Working of Two Strokes CI Engine

## 6.4.5 Comparison Between Four-strokes and Two-strokes Engines

Table 6.1 Comparison Between Four- and Two-strokes Engine

| Four-stroke engines | Two-strokes engines |
|---|---|
| 1. The thermodynamic cycle is completed in four strokes of the piston and two revolutions of the crankshaft. Thus, one power stroke is obtained in two revolutions of crankshaft. | 1. The thermodynamic cycle is completed in two strokes of the piston and one revolution of the crankshaft. Thus, one power stroke is obtained in one revolution of crankshaft. |
| 2. Turning moment is not so uniform during all the four strokes and hence heavier flywheel is required. | 2. Comparatively, turning moment is more uniform and hence lighter flywheel can be employed. |
| 3. The power produced for same size engine is less than two strokes engine due to one power stroke in two revolutions of crankshaft. Or for same power output engine required is heavier and bulkier. | 3. The power produced for same size engine is more than the four stroke engine due to one power stroke in each revolution of crankshaft. |
| 4. Lesser cooling and lubrication is required due to one power stroke in two revolutions and hence less wear and tear occurs. | 4. Larger cooling and lubrication is required due to one power stroke in each revolution and hence more wear and tear occurs. |
| 5. It consists of valves and valve actuating mechanism such as cam, camshaft, rocker arm, spring, valve and valve sheet. | 5. It has ports in place of valves. |
| 6. It has higher volumetric efficiency as the time available for induction of charge is more. | 6. Volumetric efficiency is lower due to lesser time available for induction. |
| 7. It has higher thermal efficiency due to complete combustion of the fuel. | 7. It has lower thermal efficiency due to partial wastage of fuel through the exhaust port and incomplete combustion. |

## 6.4.6 Comparison Between SI and CI Engines

Comparison between SI and CI engines is summarized in Table 6.2a.

Table 6.2a Comparison Between SI and CI Engines

| SI engines | CI engines |
|---|---|
| 1. It is based on Otto cycle or constant volume heat addition and rejection cycle. | 1. It is based on diesel cycle or constant pressure heat addition and constant volume heat rejection cycle. |
| 2. A high volatile, high self-ignition temperature fuel, gasoline is used. | 2. Comparatively low volatile and low self-ignition temperature fuel, diesel is used. |
| 3. A gaseous mixture of fuel and air is inducted during suction stroke. A carburettor is necessary to provide the mixture. | 3. Fuel is injected at high pressure at the end of compression stroke. A fuel pump and injector unit is used. |
| 4. Throttle controls the quantity of fuel–air mixture introduced. | 4. The quantity of fuel is regulated in pump. Air quantity is not controlled. There is quality control. |
| 5. For combustion of the charge, it requires ignition system with stark plug in combustion chamber. | 5. Auto ignition occurs due to high temperature of air resulting from high compression. |
| 6. Compression ratio ranges from 6 to 10. | 6. Compression ratio ranges from 16 to 20. |
| 7. Due to light weight and homogeneous combustion, they are high speed engines. | 7. Due to heavy weight and heterogeneous combustion, they are comparatively low speed engines. |
| 8. It has lower thermal efficiency due to lower compression ratio but delivers more power for same compression ratio. | 8. It has higher thermal efficiency due to high compression ratio and delivers lesser power for the same compression ratio. |

## 6.4.7 Comparison Between Otto Cycle and Diesel Cycle

Comparison between Otto cycle and diesel cycle is summarized in Table 6.2b.

Table 6.2b Comparison Between Otto Cycle and Diesel Cycle

| Otto cycle | Diesel cycle |
|---|---|
| 1. In Otto cycle, heat added and rejected at constant volume. | 1. In diesel cycle, heat is added at constant pressure and heat is rejected at constant volume. |
| 2. For same compression ratio, Otto cycle is more efficient than that of diesel cycle. | 2. Compression ratio of diesel cycle is more than that of Otto cycle. |
| 3. Otto cycle is used in S.I engines. | 3. Diesel cycle is used in CI engines. |

16 For isentropic compression process $1-2, \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = (r_k)^{\gamma-1}; \quad T_2 = T_1(r_k)^{\gamma-1}$

For constant volume heat addition process $2-3, \frac{T_3}{T_2} = \frac{P_3}{P_2}; T_3 = T_2\frac{P_3}{P_2} = T_3 = T_1 r_p (r_k)^{\gamma-1}$

For constant pressure heat addition process $3-4, \frac{T_4}{T_3} = \frac{V_4}{V_3} = r_c; T_4 = T_3 r_c = T_1 r_p (r_k)^{\gamma-1} r_c$

For isentropic expansion process $4-5, T_5 = T_4\left(\frac{V_4}{V_5}\right)^{\gamma-1} = T_1 r_p (r_k)^{\gamma-1} r_c \left(\frac{V_4}{V_5}\right)^{\gamma-1}$

Now $\frac{V_4}{V_5} = \frac{V_4}{V_1} = \frac{V_4}{V_3} \times \frac{V_3}{V_1} = \frac{V_4}{V_3} \times \frac{V_2}{V_1} = \frac{r_c}{r_k}$

Hence, $T_5 = T_1 r_p (r_k)^{\gamma-1} r_c \left(\frac{r_c}{r_k}\right)^{\gamma-1} = T_1 r_p r_c^{\gamma}$; and $\eta_{th} = 1 - \frac{1}{r_k^{\gamma-1}}\left[\frac{r_p r_c^{\gamma} - 1}{(r_p - 1) + \gamma \cdot r_p (r_c - 1)}\right]$

**Example 6.6:** An air standard dual cycle has a compression ratio of 18 and compression starts at 0.1 MPa and 300 K. The maximum pressure is 8 MPa. The heat transferred to air at constant pressure is equal to that at constant volume. Determine (i) temperatures and pressures at the end points of all the processes, (ii) cycle efficiency, and (iii) mean effective pressure. $C_p = 1.005$ kJ/kg, $C_v = 0.718$ kJ/kg K, $\gamma_{air} = 1.4$.

**Solution:**

Given: $r_k = \frac{V_1}{V_2} = 18$, $P_1 = 0.1$ MPa, $T_1 = 300$K, $P_3 = P_4 = 8$MPa, $Q_1 = Q_2$ where $Q_1$ is heat added at constant volume and $Q_2$ is heat added at constant pressure

$$P_1V_1^{\gamma} = P_2V_2^{\gamma}; P_2 = P_1\left(\frac{V_1}{V_2}\right)^{\gamma} = 100\,(18)^{1.4} = 5.72\,\text{MPa}$$

$$V_2 = \frac{V_1}{18} = \frac{RT_1}{18P_1} = \frac{0.287 \times 300}{18 \times 100} = 0.0478\,\text{m}^3 = V_3$$

$$V_1 = V_5 = 0.861\,\text{m}^3;\ T_2 = T_1\left(\frac{V_1}{V_2}\right)^{\gamma-1} = 300\,(18)^{0.4} = 953.3\,\text{K}$$

$\frac{P_2}{T_2} = \frac{P_3}{T_3}$ for constant volume process $2-3$

$$T_3 = \frac{P_3}{P_2}T_2 = \frac{8 \times 10^3}{5720} \times 953.3 = 1{,}333.33\,\text{K}$$

$$Q_1 = C_v(T_3 - T_2) = 0.718\,(1{,}333.33 - 953.3) = 272.86 = Q_2 = C_p(T_4 - T_3)$$

$$T_4 = \frac{272.86}{1.005} + 1{,}333.33 = 1{,}604.83\,\text{K}$$

$\frac{V_4}{T_4} = \frac{V_3}{T_3}$ for constant pressure process $3-4$; $V_4 = \frac{V_3}{T_3}$

$$T_4 = \frac{0.0478}{1{,}333.33} \times 1{,}604.83 = 0.057\,\text{m}^3$$

$$P_4V_4^{\gamma} = P_5V_5^{\gamma}; P_4 = \left(\frac{0.057}{0.861}\right)^{1.4} \times 8 \times 10^3 = 0.178\,\text{MPa}$$

$$T_5 = \frac{P_5}{P_1}T_1 = \frac{0.178}{0.1} \times 300 = 534\,\text{K}$$

Hence,

$$\begin{cases} P_1 = 0.1\text{ MPa}, T_1 = 300\text{ K}, V_1 = 953.3\text{ K} \\ P_2 = 5.72\text{ MPa}, T_2 = 953.3\text{ K}, V_2 = 0.0478\text{ m}^3 \\ P_3 = 8\text{ MPa}, T_3 = 1{,}333.33\text{ K}, V_3 = 0.0478\text{ m}^3 \\ P_4 = 8\text{ MPa}, T_4 = 1{,}604.83\text{ K}, V_4 = 0.057\text{ m}^3 \\ P_5 = 0.17\text{ MPa}, T_5 = 5.4\text{ K}, V_5 = 0.861\text{ m}^3 \end{cases}$$

$$Q_{out} = C_v(T_5 - T_1) = 0.718\,(534 - 300) = 168.012\text{ kJ/kg}$$

$$Q_1 = Q_2 = C_v(T_3 - T_2) = 0.718\,(1{,}333.33 - 953.3) = 272.86$$

$$W_{net} = Q_1 + Q_2 - Q_{out} = 2 \times 272.86 - 168.012 = 377.708\text{ kJ/kg}$$

$$\eta_{th} = \frac{W_{net}}{Q_1 + Q_2} = \frac{377.708}{545.72} = 0.6921 = 69.21\%$$

$$P_m = \frac{W_{net}}{V_1 - V_2} = \frac{377.708}{0.861 - 0.047} = 464.01\,\text{kN/m}^2$$

## 6.9 ENGINE PERFORMANCE PARAMETERS

There are several parameters to indicate the performance of an IC engine, for example, indicated thermal efficiency ($\eta_{ith}$), brake thermal efficiency ($\eta_{bth}$), mechanical efficiency ($\eta_{mech}$), volumetric efficiency ($\eta_v$), relative efficiency of efficiency ratio ($\eta_{rel}$), mean effective pressure ($P_m$), mean piston speed ($S_p$), specific power output ($P_s$), specific fuel consumption (sfc), and air fuel ratio ($A/F$).

***Indicated Thermal Efficiency:*** It is ratio of energy in the indicated diagram ($I_p$) to the input fuel energy.

$$\eta_{ith} = \frac{i_p\,[\text{kJ/s}]}{\text{Mass of fuel [kg/s]} \times \text{Calorific value of the fuel [kJ/kg]}}$$

***Brake Thermal Efficiency:*** It is ratio of energy in brake power ($B_p$) to the input fuel energy. Brake power is obtained by subtraction of friction losses from indicated power.

$$\eta_{bth} = \frac{b_p\,[\text{kJ/s}]}{\text{Mass of fuel}[\text{kg/s}] \times \text{Calorific value of the fuel}[\text{kJ/kg}]}$$

***Mechanical Efficiency:*** It is ratio of the brake power to the indicated power.

$$\eta_{mech} = \frac{b_p}{i_p} = \frac{b_p}{b_p + f_p}; \text{ where } f_p \text{ is a friction power}$$

***Volumetric Efficiency:*** It is ratio of the volume of air inducted at ambient conditions to the swept volume of the engine.

$$\eta_v = \frac{\text{Volume of charge aspirated per stroke at ambient conditions}}{\text{Stroke volume}}$$

***Relative Efficiency or Efficiency Ratio:*** It is ratio of the thermal efficiency of actual cycle and the ideal cycle.

$$\eta_{rel} = \frac{\text{Actual thermal efficiency}}{\text{Air standard efficiency}}$$

***Mean Effective Pressure:*** It is the average pressure inside the cylinder of an IC engine on the measured power output. For any particular engine operating at given speed and power output, there will be a specific indicated mean effective pressure and corresponding brake mean effective pressure. They can be expressed as

$$P_{im} = \frac{60{,}000 \times i_p}{lAnk} \quad \text{and} \quad P_{bm} = \frac{60{,}000 \times b_p}{lAnk}$$

where $P_{im}$ = Indicated mean effective pressure (N/m$^2$)
$P_{bm}$ = Brake mean effective pressure (N/m$^2$)
$l$ = Stroke length (m)
$A$ = Cross-sectional area of piston (m$^2$)
$N$ = Speed in revolution per minute
$n$ = Number of power strokes ($N$/2 for four strokes engine and $N$ for two strokes engine)
$k$ = Number of cylinders

***Mean Piston Speed:*** It is defined as $S_p = 2lN$, where $l$ is stroke length in m and $N$ is the rotational speed of the crankshaft in rpm.

***Specific Power Output:*** It is defined as the power output per unit piston area.

$$P_s = \frac{b_p}{A},$$

where $b_p$ brake power in kJ and $A$ is piston area in m$^2$.

***Specific Fuel Consumption:*** It is inversely proportional to thermal efficiency. It is ratio of fuel consumption per unit time and the power.

***Air–fuel Ratio:*** This is ratio of mass of air and fuel.

**Example 6.7:** The following data were noted for a four-cylinder, four-stroke engine: Diameter = 101 mm, stroke = 114 mm, speed = 1,600 rpm, fuel consumption = 0.204 kg/min, heating value of fuel = 41,800 kJ/kg. Difference in either side of the brake pulley = 378 N, brake circumference = 3.35 m. Assume mechanical efficiency = 83%. Calculate (i) brake thermal efficiency, (ii) indicated thermal efficiency, (iii) mean effective pressure of cylinder, and (iv) fuel consumption per brake power.

**Solution:**

Brake power, $(b_p) = \dfrac{2\pi NT}{60{,}000} = \dfrac{2\pi NRW}{60{,}000}$; where $N$ is speed in rotation per minute, $T$ is braking torque, $R$ is radius, $W$ is braking load.

$$b_p = \frac{3.35 \times 1{,}600 \times 378}{60{,}000} = 33.77\,\text{kW};$$

Brake thermal efficiency, $(\eta_b) = \dfrac{b_p \times 60}{w_f \times \text{H.V}}$; where $w_f$ is fuel consumption in kg/min and HV is heating value of fuel.

$$\eta_b = \frac{33.77 \times 60}{0.204 \times 41{,}800} = 23.8\%$$

Indicated thermal efficiency, $(\eta_i) = \dfrac{\eta_b}{\eta_{mech}} = \dfrac{0.237}{0.83} \times 100 = 28.5\%$

Indicated power, ( ) $\dfrac{2PlAN/2}{60{,}000}$; where $P_i$ is indicated mean effective pressure, $l$ is stroke length, A is internal cross-sectional area of cylinder.

$$\text{m.e.p., } P_i = \frac{60{,}000 \times b_p}{2lAN\eta_{mech}} = \frac{60{,}000 \times 33.77}{2 \times 0.114 \times \dfrac{\pi(0.101)^2}{4} \times 1{,}600 \times 0.83}$$

$$= 835.75\,\text{kPa}$$

$$\text{Brake specific fuel consumption} = \frac{w_f \times 60}{b_p} = \frac{0.204 \times 60}{33.77} = 0.36\,\text{kg/bkWh}$$

## SUMMARY

The chapter can be summarized as follows:

- The heat engine, in which the combustion takes place inside the cylinder or the product of combustion (flue gas) directly goes to the cylinder and the heat energy of the flue gas is converted into mechanical energy, is known as Internal Combustion Engine (IC Engine).
- In four strokes of a spark ignition engine, the cycle of operations is completed in four strokes of the piston or two revolutions of the crankshaft.

3. Differentiate SI engine and CI engine.
4. Explain the fundamental differences between Otto cycle and diesel cycle mentioning the advantages over each other.
5. What are the fundamental differences between two stroke and four stroke engines?
6. Explain the structure and working of four stroke petrol engine with a neat sketch.
7. Explain the structure and working of four stroke diesel engine with a neat sketch.
8. What is scavenging? Explain the structure and working of two stroke petrol engine.
9. What is supercharging? Explain the structure and working of two stroke diesel engine.
10. Explain the valve timing diagram of four stroke petrol and diesel engines.
11. Derive an expression for efficiency of Otto cycle.
12. Explain the working of dual cycle with the help of $P$–$V$ and $T$–$s$ diagrams. Derive an expression for air standard efficiency of dual cycle in terms of compression ratio, pressure ratio, cut-off ratio and adiabatic index.
13. Write down working of two stroke petrol engine with neat sketch.

## PROBLEMS FOR PRACTICE

1. In an air standard Otto cycle, the pressure and temperature at the start of compression stroke are 1 bar and 30°C, respectively. The temperature at the end of compression is 270°C and heat addition at constant volume is 2,000 kJ. Calculate: (i) thermal efficiency, (ii) net work per kg of air, (iii) maximum temperature in the cycle, and (iv) mean effective pressure.
2. In an Otto cycle, air at 1 bar and 300 K is compressed isentropically until the pressure rises to 16 bar. The heat is added at constant volume until the pressure rises to 30 bar. Calculate the air standard efficiency, and mean effective pressure of the cycle. Take $C_v = 0.717$ kJ/kg K; $R = 8.314$ kJ/kg mole.
3. In an air standard diesel cycle, the temperatures at the start and at the end of compression stroke are 298 and 800 K, respectively. The energy added at constant pressure is 800 kJ/kg of air. Determine: (i) compression ratio, (ii) cut-off ratio, (iii) maximum cycle temperature, and (iv) thermal efficiency. Assume $C_p$=1.005 kJ/kg.
4. A diesel engine has a compression ratio of 16 and cut-off takes place at 7% of the stroke. Find the air standard efficiency.
5. In an ideal duel cycle, the compression ratio is 12 and maximum pressure is limited to 80 bar. If the heat supplied is 2,000 kJ/kg, find the temperature and pressure at all cardinal points and the cycle efficiency. The pressure and temperature of air at the commencement of compression are 1 bar and 90°C, respectively. Assume $C_p$ = 1.005 kJ/kg K and $C_v$ =0.717 kJ/kg K of air.
6. A dual cycle operates with a compression ratio $r_k$ =10 and cut-off ratio 1.6. The maximum pressure is given by $P_{max} = 60P_1$, where $P_1$ is the pressure before compression. Assume indices of compression and expansion as 1.4, find the mean effective pressure in terms of $P_1$.
7. The following readings were taken during the test of four stroke single cylinder petrol engine:

   Load on brake drum = 50 kg; Diameter of brake drum = 1,250 mm

   Spring balance reading = 7 kg; Engine speed = 450 rpm

   Fuel consumption = 4 kg/h; Calorific value of fuel = 43,000 kJ/kg

   Calculate: (i) indicated thermal efficiency, and (ii) brake thermal efficiency. Assume mechanical efficiency as 70%.

8. [illegible]

   Indicated power = 37 kW; Frictional power = 6 kW;

   Brake specific fuel consumption = 0.28 kg/KWh; Calorific value of fuel = 44,300 kJ/kg

   Calculate: (i) mechanical efficiency, (ii) brake thermal efficiency, and (iii) indicated thermal efficiency.

9. During testing of single cylinder two stroke petrol engine, following data were obtained: brake torque = 640 N m; cylinder diameter = 21 cm, speed = 250 rpm; stroke = 28 cm; m.e.p. = 5.6 bar; oil consumption = 8.16 kg/h; C.V. = 42,705 kJ/kg. Determine (i) mechanical efficiency, (ii) indicated thermal efficiency, and (iii) brake specific fuel consumption.
10. Following readings were taken during test of single cylinder four stroke engine:

    Cylinder diameter = 250 mm; stroke length = 400 mm; m.e.p. = 6.5 bar; engine speed = 250 rpm; net load on brake = 1,080 N; effective diameter of brake = 1.5 m; fuel used per hour = 10 kg; calorific value of fuel = 44,300 kJ/kg.

    Calculate: (i) indicated horse power, (ii) brake horse power, (iii) mechanical efficiency, and (iv) indicated thermal efficiency.
11. In an ideal diesel cycle, the temperatures at the beginning and at the end of compression are 57 and 603°C, respectively. The temperatures at the beginning and at the end of expansion are 1,959 and 870°C, respectively. Determine the ideal efficiency of the cycle if pressure at the beginning is 1 bar. Calculate maximum pressure in the cycle.
12. In an air standard Otto cycle, the compression ratio is 10 and begins at 37.8°C, 1 bar and maximum temperature of the cycle is 1,060°C. Determine: (i) heat supplied per kg of air, (ii) work done per kg of air, (iii) maximum pressure of the cycle, and (iv) the thermal efficiency.
13. In an air standard diesel cycle, the compression ratio is 15 and pressure and temperature of the air at the beginning of the compression are 1 bar and 288 K. The peak temperature in the cycle is 2,700 K. Calculate (i) heat supplied, (ii) work done, (iii) cycle efficiency, (iv) peak pressure of the cycle, and (v) cut-off ratio, (vi) m.e.p.
14. A gas engine working on four stroke cycle has a cylinder of 250 mm diameter, length of stroke 450 mm and is running at 180 rpm. Its mechanical efficiency is 80%; mean effective pressure is 0.65 MPa, Find: (i) indicated power, (ii) brake power, and (iii) friction power.
15. A four stroke single cylinder petrol engine has a bore of 150 mm and stroke of 250 mm. At 500 rpm and full load, the net load on friction brake is 435 N and torque arm is 0.45 m. The indicator diagram gives a net area of 580 mm² and a length of 70 mm with a spring rating of 0.85 bar/mm². Determine indicated power, brake power, and mechanical efficiency.
16. Following observations were made during a trial on four stroke diesel engine. Cylinder diameter = 250 mm, stroke = 400 mm, speed = 250 rpm, brake load = 70 kg, brake drum diameter = 2 m, m.e.p. = 6 bar, diesel oil consumption = 0.1 m³/min., specific gravity of fuel = 0.78, C.V. = 43,900 kJ/kg. Determine (i) IP, (ii) BP, (iii) FP, (iv) mechanical efficiency, (v) brake thermal efficiency, and (vi) indicated thermal efficiency.
17. Following data were collected from a four stroke single cylinder IC engine at full load. Bore = 200 mm, stroke = 280 mm, speed = 300 rpm, m.e.p. = 5.6 bar, torque = 250 N m. Oil consumption = 4.2 kg/h, C.V. = 41,000 kJ/kg. Determine (i) mechanical efficiency, (ii) indicated thermal efficiency, and (iii) brake thermal efficiency.

Answers

1. (c), 2. (a), 3. (c), 4. (b), 5. (a), 6. (d), 7. (d), 8. (c), 9. (d), 10. (a), 11. (d), 12. (d), 13. (a), 14. (a), 15. (c).



## REVIEW QUESTIONS

1. What do you mean by heat transfer? Explain its applications in engineering.
2. Explain the different modes of heat transfer.
3. Derive the expression for heat flow in steady state conduction without heat generation using Fourier Law.
4. Explain Newton's law of cooling and derive the heat flow in convection.
5. Explain Stefan and Boltzmann's law and derive the heat flow in convection.
6. What do you mean by heat exchangers? Explain the various types of heat exchanger according to flow of cold and hot liquids/gases with their applications.

## PROBLEMS FOR PRACTICE

1. The inner surface of a plane brick wall is at 80°C and the outer surface is at 30°C. Calculate the rate of heat transfer per $m^2$ of surface area of the wall, which is 280 mm thick. The thermal conductivity of the brick is 0.75 W/m K.
2. A steel tank of wall thickness 10 mm contains water at 90°C. Calculate the rate of heat loss per $m^2$ of tank surface area when the atmospheric temperature is 15°C. The thermal conductivity of mild steel is 55 W/m K, and the heat transfer coefficients for the inside and outside of the tank are 2,550 and 24 W/$m^2$K, respectively. Calculate also the temperature of the outside surface of the tank.
3. A furnace wall consists of 100 mm thick refractory brick and 800 mm thick insulating firebrick separated by an air gap. The outside wall is covered with a 20 mm thickness of plaster. The inner surface of the wall is at 1,100°C and the room temperature is 26°C. Calculate the rate at which heat is lost per $m^2$ of wall surface. The heat transfer coefficient from the outside wall surface to the air on the room is 22 W/$m^2$K, and the resistance to heat flow of the air gap is 0.16 K/W. The thermal conductivity of refractory brick, insulating firebrick, and plaster are 1.5, 0.25 and 0.13 W/m K, respectively. Calculate also each interface temperature of the outside of the wall.
4. A steel pipe of 100 mm bore and 10 mm wall thickness, carrying steam at 250°C, is insulated with 30 mm of a moulded high temperature diatomaceous earth covering. This covering is in turn insulated with 60 mm of asbestos felt. If the atmospheric temperature is 22°C, calculate the rate at which heat is lost by the steam per metre length of pipe. The heat transfer coefficients for the inside and outside surfaces are 520 and 28 W/$m^2$K, respectively, and the thermal conductivity of steel, diatomaceous earth and asbestos felt are 54, 0.12 and 0.09 W/m K, respectively. Calculate also the temperature of the outside surface.
5. A small hemispherical oven is built of an inner layer of insulating firebrick 110 mm thick, and an outer covering 80% magnesia 45 mm thick. The inner surface of the oven is 850°C and the heat transfer coefficient for the outside surface is 12 W/$m^2$K; the room temperature is 26°C. Calculate the heat loss through the hemisphere, if the inside radius is 1.0 m. Take the thermal conductivities of firebrick and 80% magnesia as 0.32 and 0.06 W/m K.

# 8 Refrigeration and Air Conditioning

**Chapter Objectives**

**In this chapter, you will learn about:**

- Working principles of refrigerator and heat pump
- Types of refrigeration systems
- Types of refrigerants
- Type of refrigerators
- Type of room air conditioners

## 8.1 INTRODUCTION

Initially, the main purpose of refrigeration was to conserve foods. The Chinese were the first to find out that ice increased the life and improved the taste of drinks and for centuries Eskimos have conserved food by freezing it. At the beginning of the 19th century, it had been observed that the growth of microorganisms is temperature dependent, that growth declines as temperature falls and that growth becomes very slow at temperatures below +10°C. As a consequence of this knowledge, it was now possible to use refrigeration to conserve foodstuffs and natural ice came into use for this purpose.

The idea of air conditioning started before a machine was created to produce the cooling effect desired. The first attempt at building an air conditioner was made by John Gorrie (1803–1855), an American physician, in Apalachicola, Florida. During his practice there in the 1830s, Gorrie created an ice-making machine that essentially blew air over a bucket of ice for cooling hospital rooms of patients suffering from malaria and yellow fever.

## 8.2 REFRIGERATOR AND HEAT PUMP

Clausius statement of the Second Law of Thermodynamics: *It is impossible to construct a device that, operating in a cycle, has no effect other than the transfer of heat from a cooler to a hotter body*. Thus, the Clausius statement tells us that heat will not flow from cold to hot regions without assistance of outside agents. The devices that provide this assistance are called *refrigerators* and *heat pumps*. The working of refrigerator and heat pump is shown in Figure 8.1. The distinction

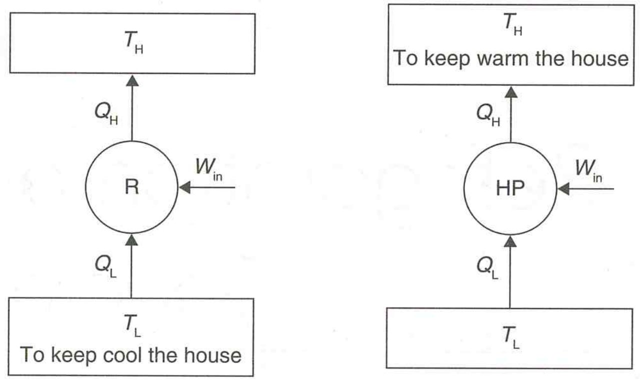



**Figure 8.1** Working of Refrigerator and Heat Pump

between refrigerator and heat pump is one of purpose more than technique. The refrigeration unit transfers heat from cold to hot regions for the purpose of cooling the cold region while the heat pump does the same thing with the intent of heating the hot region.

The performance of the refrigerators and heat pump is expressed in terms of the Coefficient of Performance (COP), which is defined as

$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{in}}$$

$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{in}}$$

$$COP_{HP} = COP_R + 1$$

***Tones of Refrigeration (TR):*** The cooling effect produced is quantified as tons of refrigeration, also referred to as 'chiller tonnage'.

$$TR = Q \times C_p \times (T_i - T_o)/3{,}024 = 210 \text{ kJ/min or } 3.5 \text{ kJ/s}.$$

where $Q$ Mass flow rate of coolant in kg/h
$C_p$ Coolant specific heat in kcal/kg °C
$T_i$ Inlet temperature of coolant to evaporator (chiller) in °C
$T_o$ Outlet temperature of coolant from evaporator (chiller) in °C

1 TR of refrigeration = 3,024 kcal/h heat rejected
Power of refrigerator = $Q_L$/C.O.P
Capacity of refrigeration plant = Heat removal rate in tons

The heat absorbed from a body or space to be cooled, equivalent to the latent heat of fusion of 1 ton of ice from 0°C in 24 hours is called 1 ton of refrigeration.

## 8.3 COMPONENTS OF REFRIGERATION SYSTEM

The five basic components of a refrigeration system are as follows:

1. Evaporator
2. Compressor
3. Condenser
4. Expansion valve
5. Refrigerant; to conduct the heat from the product in order for the refrigeration cycle to operate successfully each component must be present within the refrigeration system.

### 8.3.1 Evaporator

The purpose of the evaporator is to remove unwanted heat from the product via the liquid refrigerant. The liquid refrigerant contained within the evaporator is boiling at a low pressure. The level of this pressure is determined by two factors:

1. The rate at which the heat is absorbed from the product to the liquid refrigerant in the evaporator.
2. The rate at which the low pressure vapour is removed from the evaporator by the compressor to enable the transfer of heat, the temperature of the liquid refrigerant must be lower than the temperature of the product being cooled. Once transferred, the liquid refrigerant is drawn from the evaporator by the compressor via the suction line. When leaving the evaporator coil the liquid refrigerant is in vapour form.

### 8.3.2 Compressor

The purpose of the compressor is to draw the low-temperature, low-pressure vapour from the evaporator via the suction line. Once drawn, the vapour is compressed. When vapour is compressed it rises in temperature. Therefore, the compressor transforms the vapour from a low-temperature vapour to a high-temperature vapour, in turn increasing the pressure. The vapour is then released from the compressor into the discharge line.

### 8.3.3 Condenser

The purpose of the condenser is to extract heat from the refrigerant to the outside air. The condenser is usually installed on the reinforced roof of the building, which enables the transfer of heat. Fans mounted above the condenser unit are used to draw air through the condenser coils. The temperature of the high-pressure vapour determines the temperature at which the condensation begins. As heat has to flow from the condenser to the air, the condensation temperature must be higher than that of the air. The high-pressure vapour within the condenser is then cooled to the point where it becomes a liquid refrigerant once more, whilst retaining some heat. The liquid refrigerant then flows from the condenser into the liquid line.

### 8.3.4 Expansion Valve

Within the refrigeration system, the expansion valve is located at the end of the liquid line, before the evaporator. The high-pressure liquid reaches the expansion valve, having come from the condenser. The valve then reduces the pressure of the refrigerant as it passes through the orifice, which is located inside the valve. On reducing the pressure, the temperature of the refrigerant also decreases to a level below the surrounding air. This low-pressure, low-temperature liquid is then pumped into the evaporator.

## 8.4 TYPES OF REFRIGERATION SYSTEMS

Broadly, the refrigeration systems can be categorized as

- Air-refrigeration system.
- Vapour compression refrigeration system.
- Absorption refrigeration system.

### 8.4.1 Air-refrigeration System

#### Reversed Carnot Cycle

Reversed Carnot cycle is shown in Figure 8.2. It consists of the following processes.

***Process 1–2:*** Absorption of heat by the working fluid from refrigerator at constant low temperature $T_L$ during isothermal expansion.

***Process 2–3:*** Isentropic compression of the working fluid with the aid of external work. The temperature of the fluid rises from $T_L$ to $T_H$.

***Process 3–4:*** Isothermal compression of the working fluid during which heat is rejected at constant high temperature $T_H$.

***Process 4–1:*** Isentropic expansion of the working fluid. The temperature of the working fluid falls from $T_H$ to $T_L$.

***COP of Refrigerator***

$$\text{COP} = \frac{\text{Heat absorbed}}{\text{Work supplied}} = \frac{\text{Heat absorbed}}{\text{Heat rejected} - \text{Heat absorbed}}$$

$$= \frac{T_L(S_2 - S_1)}{T_H(S_2 - S_1) - T_L(S_2 - S_1)} = \frac{T_L}{T_H - T_L}$$

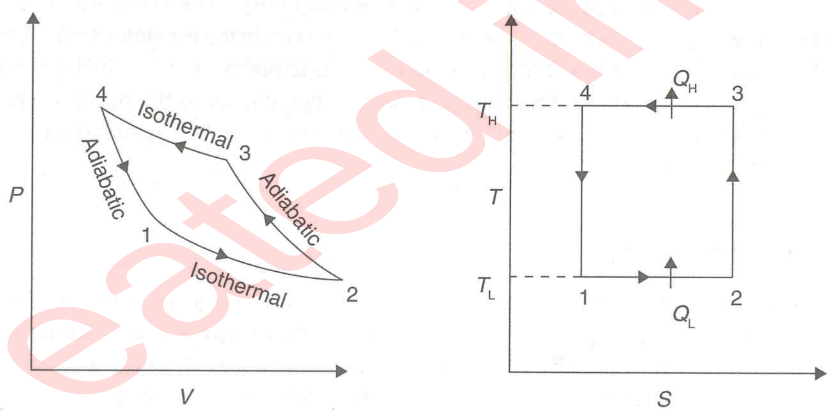



Figure 8.2 *P–V* and *T–S* Diagrams for Reversed Carnot Cycle

Practical use of the reversed Carnot cycle is not possible for refrigeration purpose as the isentropic process requires very high speed operation, whereas the isothermal process requires very low speed operation.

#### Bell–Coleman Cycle or Reversed Brayton Cycle

In this system, air is taken into the compressor from atmosphere and compressed and then the hot compressed air is cooled in heat exchanger up to the atmospheric temperature. The cooled air is then expanded in an expander. The temperature of the air coming out from the expander is below the atmospheric temperature due to isentropic expansion. The low temperature air coming out from the expander enters into the evaporator and absorbs the heat. The cycle is repeated again and again. The working of reversed Brayton cycle is represented on *P–V* and *T–S* diagrams in Figure 8.3.

***Process 1–2:*** Suction of air into the compressor.

***Process 2–3:*** Isentropic compression of air by the compressor.

***Process 3–4:*** Discharge of high pressure air from the compressor into the heat exchanger. (The reduction in volume of air from $V_3$ to $V_4$ is due to the cooling of air in the heat exchanger).

***Process 4–1:*** Isentropic expansion of air in the expander.

***Process 1–2:*** Absorption of heat from the evaporator at constant pressure and suction of air into the compressor.

$$\text{COP} = \frac{\text{Net refrigeration effect}}{\text{Net work supplied}}$$

Work done per kg of air for the isentropic compression process 2–3 is given by,

$$W_{comp} = C_p(T_3 - T_2)$$

Work developed per kg of air for the isentropic expansion process 4–1 is given by,

$$W_{exp} = C_p(T_4 - T_1)$$

$$W_{net} = (W_{comp} - W_{exp}) = C_p(T_3 - T_2) - C_p(T_4 - T_1)$$

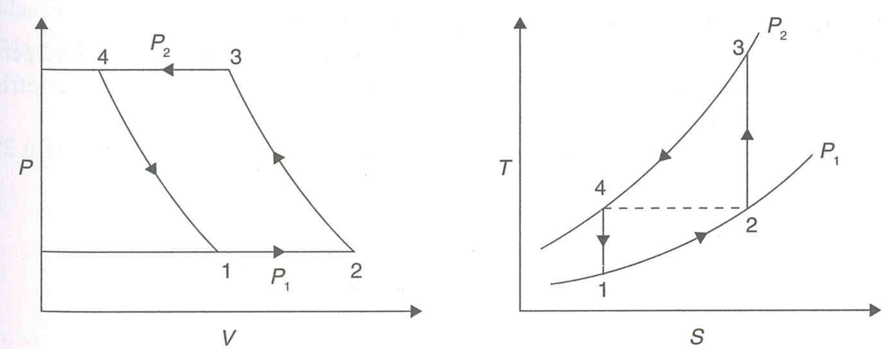



Figure 8.3 Reversed Brayton Cycle

### 8.4.2 Vapour Compression Refrigeration System

A simple vapour compression refrigeration system consists of the following equipments (Figure 8.4):

- Compressor
- Condenser
- Expansion valve
- Evaporator

The low temperature and low pressure vapour is compressed by a compressor to high temperature and high pressure vapour. This vapour is then condensed into condenser at constant pressure and then passed through the expansion valve. Here, the vapour is throttled down to a low pressure liquid and passed through an evaporator, where it absorbs heat from the surroundings and vaporizes into low pressure vapour. The cycle then repeats again and again. The heat and work interaction in vapour compression process takes place in following way:

- Compressor requires work ($W$). The work is supplied to the system.
- During condensation, heat $Q_H$ the equivalent of latent heat of condensation, etc. is removed from refrigerant.
- During evaporation, heat $Q_L$ equivalent to latent heat of vaporization is absorbed by the refrigerant.
- There is no exchange of heat during throttling process through the expansion valve as this process occurs at constant enthalpy.

***Process A–B:*** Heat absorption in evaporator at constant pressure. The final state depends on the

### Advantages and Disadvantages of Vapour Refrigeration Systems Over Air-refrigeration Systems

*Advantages*

- Vapour refrigeration system has higher C.O.P than the air-refrigeration system.
- Vapour refrigeration system has easer controllable expansion process.
- It has low running cost.
- It requires smaller evaporator.

*Disadvantages*

- Vapour refrigeration system has higher capital cost.
- In vapour refrigeration, system leakage problem may occur.

### 8.4.3 Absorption Refrigeration Cycle

The absorption cycle is a process by which refrigeration effect is produced through the use of two fluids and some quantity of heat input, rather than electrical input as in the more familiar vapour compression cycle. Both vapour compression and absorption refrigeration cycles accomplish the removal of heat through the evaporation of a refrigerant at a low pressure and the rejection of heat through the condensation of the refrigerant at a higher pressure. The method of creating the pressure difference and circulating the refrigerant is the primary difference between the two cycles. The vapour compression cycle employs a mechanical compressor to create the pressure differences necessary to circulate the refrigerant. In the absorption system, a secondary fluid or absorbent is used to circulate the refrigerant. Because the temperature requirements for the cycle fall into the low-to-moderate temperature range, and there is significant potential for electrical energy savings, absorption would seem to be a good prospect for geothermal application.

Absorption machines are commercially available today in two basic configurations. For applications above 32°F (primarily air conditioning), the cycle uses lithium bromide as the absorbent and water as the refrigerant. For applications below 32°F, an ammonia/water cycle is employed with ammonia as the refrigerant and water as the absorbent.

## 8.5 TYPE OF REFRIGERANTS

Research on use of refrigerant is continuously going on due to adverse effect on depletion of ozone layer. The production of many refrigerants will soon end, including R-22 and R-123 in accordance to the requirements of the Montreal Protocol. Suppliers currently offer a range of refrigerants based on chiller type, capacity, and regulatory requirements. The refrigerants can be classified into the following classes:

- *Halocarbons:* Halocarbon refrigerants are all synthetically produced and were developed as the Freon family of refrigerants. Some of the refrigerants in this class are as follows:
  - CFCs: R11, R12, R113, R114, R115
  - HCFCs: R22, R123
  - HFCs: R134a, R404a, R407C, R410a
- *Inorganic refrigerants:* Following refrigerants are used as inorganic refrigerants: carbon dioxide, water, ammonia, air, sulphur dioxide.
- *Zeotropic refrigerants:* A stable mixture of two or several refrigerants whose vapour and liquid phases retain identical compositions over a wide range of temperatures.
- *Hydrocarbon refrigerants:* Following hydrocarbon gases have been used as refrigerants in industrial, commercial, and domestic applications:
  - R170, ethane ($C_2H_6$)
  - R290, propane ($C_3H_3$)
  - R600, butane ($C_4H_{10}$)
  - R600a, isobutane ($C_4H_{10}$)
  - Blends of the above gases

## 8.6 TYPES OF REFRIGERATORS

A refrigerator maintains the temperature slightly higher than the freezing point of the water. There is a freezer which maintains the temperature below the freezing point of water. As far as the classification of refrigerators is concerned, it can be widely classified into four classes. They are top-mount freezer refrigerator, side-by-side refrigerators, freezer on bottom, and French door refrigerators.

### 8.6.1 Top-mount Refrigerators

This is the most common type of refrigerator. The refrigerator has wider shelves in both the freezer and fridge. In this refrigerator, the freezer is placed at the top level. Generally, the height of the freezer varies in between 60 and 69 in., which is why they tend to offer more storage capacity as compared to the other models.

Following are the advantages and disadvantages of top-mount refrigerators:

- *Advantages:* Familiar design; lower price than more feature-rich styles.
- *Disadvantages:* Among the least flexible configurations (along with bottom-freezer); items in back of freezer may be difficult to reach for children and shorter adults; requires wide, deep space to allow doors to swing fully open.

### 8.6.2 Side-by-Side Mount Refrigerators

This refrigerator is more expensive as compared to the top-mount refrigerator. This is more advanced with features such as through the door cool water dispenser. With the freezer and the fridge being adjacent to each other, it allows easy access to food items that are stored. However, this refrigerator has its own disadvantage. Apart from being expensive, it tends to occupy much space in the kitchen area as both the doors need to be open. Also, the compartments are narrower and it does not fit in larger and bulky items.

5

# Steam Engine, Steam and Gas Turbines

## Chapter Objectives

**In this chapter, you will learn about:**

- Introduction to steam turbines
- Classification of steam turbine and compounding of impulse turbine
- Difference between impulse and reaction turbines
- Introduction to gas turbines
- Open cycle and close cycle gas turbine
- Application of Joule/Brayton thermodynamic cycle

## 5.1 INTRODUCTION TO STEAM POWER SYSTEMS

Steam power system is a system in which the heat energy of the steam is used to produce mechanical power. Various types of fuels (coal, diesel, natural gas, geothermal, nuclear, etc.) are used to produce the high quality of steam, i.e., superheated steam and then the thermodynamic expansion process is used to convert the heat energy of the steam into mechanical power. If mechanical power is developed in the form of shaft power and the shaft is coupled with electricity generator then the mechanical power is transformed into electrical energy. The steam engine was developed by James Watt in 1763 after that steam turbines, gas turbines, and I.C. engines came into picture.

## 5.2 STEAM ENGINES AND THEIR WORKING PRINCIPLES

A steam engine is a reciprocating heat engine that performs mechanical work by using steam as its working fluid. Steam engines are external combustion engines based on modified Rankine cycle, where the working fluid is separate from the combustion products. Water is heated in a boiler until it reaches a high pressure and temperature (superheated steam) and then expanded through piston in steam engine to do some mechanical work. The reduced-pressure steam is then released into the atmosphere or condensed and pumped back into the boiler. The working of steam engine is shown in Figure 5.1.

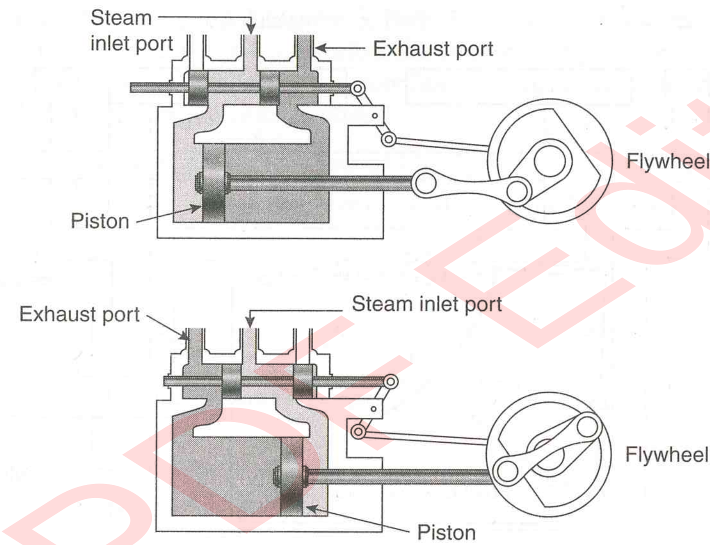



Figure 5.1 Working of Steam Engine

In a steam engine, the movement of the valve ensures that steam is admitted to and exhausted from the cylinder at the right moment. For a typical cylinder that has two ports, i.e., double acting reciprocating steam engine, the function of the valve is to admit superheated steam at one end while allowing the exhaust steam to escape at the other as shown in Figure 5.1. As a result of covering and uncovering these ports in sequence, the piston is pushed forward and backward by the high pressure steam from the boiler. To regulate the movement of the valve, a mechanical valve gear system is used.

Lap refers to the amount of overlap between the valve and the port. In slow moving locomotives, the long lap on the exhaust port gives time for the steam trapped in the cylinder to expand fully to push the piston. On the other hand, on higher speed locomotives the exhaust port is made to open early (short lap) when the valve is in mid-position thus allowing the steam to escape faster. Higher speed locomotives also have long lead which means that the admission port is already open when the piston is at the end of its movement so there is a sufficient steam pressure that will immediately push the piston back to begin its next movement.

The indicator diagram, as shown in Figure 5.2, was used by steam locomotive engineers during the steam era to estimate the locomotive's efficiency in converting the steam's energy into useful power at various speeds and cut-offs. The horizontal line at the top of the indicator diagram shows the pressure as the steam enters the cylinder. At cut-off, the pressure drops as the steam expands and does work to push against the piston. Cut-off denotes the position of the piston, at the moment the valve is closing the admission port. When the engine is working hard and slowly, long cut-off admits steam for most of the stroke of the piston. On fast running locomotives this will cause back pressure to the boiler. To avoid unnecessary back pressure, cut-off is reduced so that steam is admitted for only 20% of the piston stroke and the remainder of the stroke is due to the expansion of the high pressure steam.

After the exhaust port opens, the horizontal line at the bottom of the indicator diagram indicates the return stroke of the piston. It shows the low pressure as the steam is exhausted. The curve at the

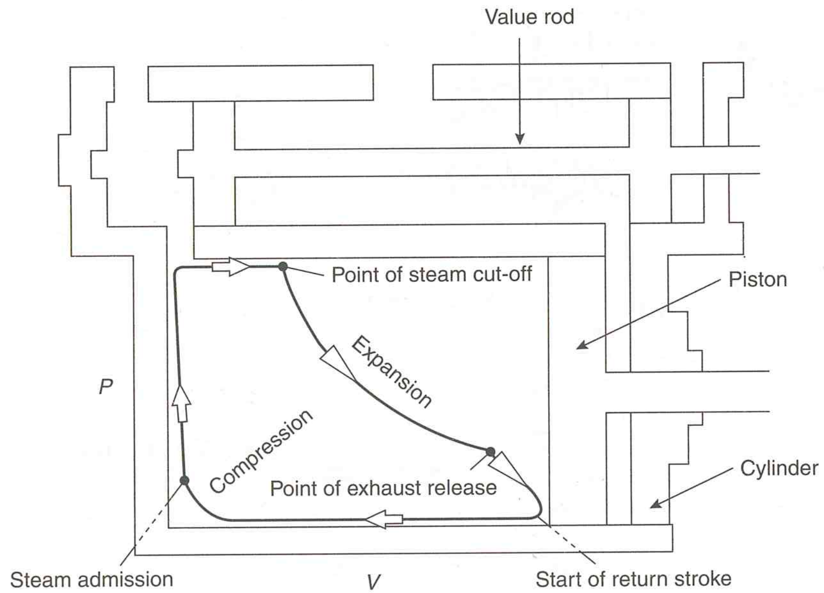



**Figure 5.2** Modified Rankine Cycle

end of the return stroke shows a pressure rise due to the compression of the remaining steam after the exhaust port has closed. As fresh steam is admitted into the cylinder, the pressure rises and the cycle repeats.

### 5.2.1 Modified Rankine Cycle: Theoretical Indicator Diagram

Theoretical indicator diagram for a steam engine is shown in Figure 5.3 without clearance volume and with clearance volume in Figure 5.4. In Figure 5.3, clearance volume is zero. Steam at boiler pressure enters into the cylinder at point 1 and cut-off at point 2. Then the steam expands inside

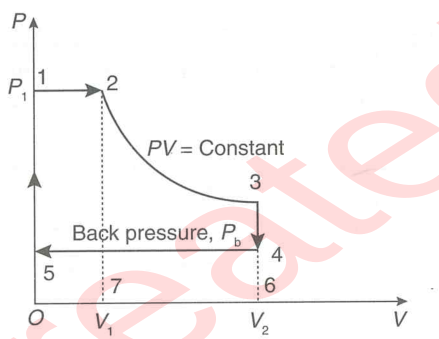



**Figure 5.3** Theoretical Indicator Diagram for Steam Engine

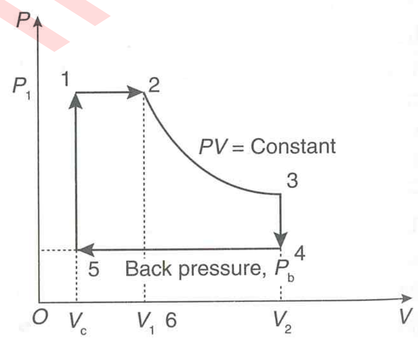



**Figure 5.4** Theoretical Indicator Diagram with Clearance Volume for Steam Engine

the cylinder isothermally from point 2 to point 3. Point 3 represents atmospheric pressure and the exhaust of the steam occurs at point 4, i.e., below the atmospheric pressure. Point 4 is known as point of release. Exhaust occurs at constant pressure line 4–5. Again steam enters into the cylinder at point 5 but suddenly pressure increases to point 1.

$$\text{Work done per cycle} = \text{Area of } 12345$$

$$= \text{Area of } 1270 + \text{Area of } 2367 - \text{Area of } 4605$$

$$= p_1V_1 + p_1V \log_e \frac{V_2}{V_1} - p_bV_2$$

$$= p_1V(1 + \log_e r) - p_bV_2 \quad \text{where } r \text{ is expansion ratio}$$

$$\text{Mean effective pressure} = \frac{\text{Work done per cycle}}{V_2}$$

$$= \frac{p_1V_1(1+\log_e r) - p_bV_2}{V_2}$$

$$= \frac{P_1}{r}(1+\log_e r) - p_b$$

Work done per cycle with clearance volume (Figure 5.4)

$$= p_1V_1 + p_1V \log_e \frac{V_2}{V_1} - p_bV_2 - (p_1 + p_b)V_c$$

$$= p_1V(1 + \log_e r) - p_bV_2 - (p_1 + p_b)\,V_c$$

where $r$ is expansion ratio and $V_c$ is clearance volume.

Mean effective pressure with clearance volume

$$= \frac{\text{Work done per cycle}}{V_2 - V_c}$$

$$= \frac{p_1V_1(\log_e r) - p_bV_2}{V_2 - V_c}$$

$$= \frac{\frac{P_1}{r}(1+\log_e r) - p_b}{V_2 - V_c}$$

#### Actual Indicator Diagram

Actual indicator diagram is shown in Figure 5.5.

In this diagram, points 1, 2, 3, 4 and 5 show actual admission pressure, point of cut-off, point of release, point of closing the exhaust port and starting of compression, and point of opening of admission port, respectively.

The area of actual indicator diagram is less than the theoretical indicator diagram.

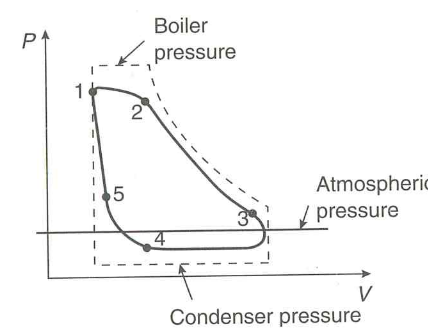



**Figure 5.5** Actual Indicator Diagram for Steam Engine

$$\text{Diagram factor} = \frac{\text{Area of actual indicator diagram}}{\text{Area of theoretical or hypothetical indicator diagram}}$$

$$= \frac{\text{Mean effective pressure of actual indicator diagram}}{\text{Mean effective pressure of theoretical or hypothetical indicator diagram}}$$

Indicated power of single acting reciprocating steam engine

$$= \frac{p_m \times L \times A \times N}{60,000} \text{kW}$$

Indicated power of double acting reciprocating steam engine

$$= \frac{2p_m \times L \times A \times N}{60,000} \text{kW}$$

where $p_m$ is a mean effective pressure, $L$ is a length of stroke, $A$ is a piston c/s area, and $N$ is r.p.m.

### 5.2.2 Rankine Cycle

The Rankine cycle is the most commonly used cycle in thermal power plants—steam engine and steam turbines. The Rankine cycle is sometimes referred to a practical Carnot cycle because when an efficient turbine is used, the $T$–$s$ diagram begins to resemble the Carnot cycle. The main difference is that heat addition and rejection are at constant pressure in the Rankine cycle and isothermal in the theoretical Carnot cycle. A pump is used to pressurize the water received from the condenser. To pump the working fluid through the cycle as a liquid requires a very small fraction of the energy needed to transport it. Carnot efficiency of about 63% compared with an actual efficiency of 42% for a modern coal-fired power station.

The working fluid in a Rankine cycle follows a closed loop and is reused continuously. Work is required to drive the pump, the working fluid being in its liquid phase at this point. By condensing the fluid, the work required by the pump consumes only 1–3% of the turbine power and contributes to a much higher efficiency for a real cycle.

#### Four Processes in the Rankine Cycle

There are four important processes in the Rankine cycle. These states are identified by numbers as shown in Figure 5.6.

***Process 1–2 (Pumping Process):*** The working fluid is pumped from low pressure to high pressure, as the fluid is a liquid at this stage the pump requires some small amount of input energy.

***Process 2–3 (Heating Process):*** The high pressure liquid enters a boiler where it is heated at constant pressure by an external heat source to become a dry saturated/superheated steam. The input energy required can be easily calculated using Mollier diagram or $h$–$s$ chart or enthalpy–entropy chart also known as steam tables.

***Process 3–4 (Expansion Process):*** The dry saturated or superheated steam expands in turbine. This decreases the temperature and pressure of the steam, and some condensation may occur. The output in this process can be easily calculated using the enthalpy–entropy chart or the steam tables.

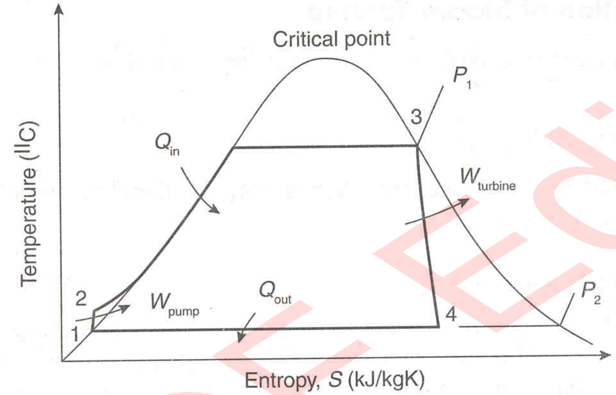



**Figure 5.6** Rankine Cycle

***Process 4–1 (Condensation Process):*** The wet vapour then enters a condenser where it is condensed at a constant temperature to become a saturated liquid.

#### Work Done in Rankine Cycle

The flow diagram of a steam power plant is shown in Figure 5.7.

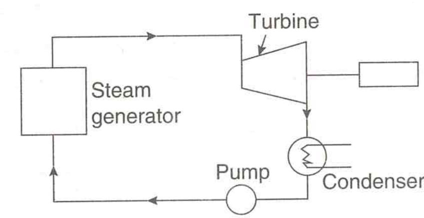



**Figure 5.7** Flow Diagram of Power Plant

Suppose

$Q_{in}$, Heat supplied to water in turbine
$Q_{out}$ Heat librated in condenser
$W_{pump}$ Work done on pump
$W_{turbine}$ Work done by turbine

The thermal efficiency of Rankine cycle can be given as

$$\eta_{thermal} = \frac{\dot{W}_{turbine} - \dot{W}_{pump}}{\dot{Q}_{in}}$$

where $W_{turbine} = h_3 - h_4$; $W_{pump} = h_2 - h_1$;

$Q_{in} = h_3 - h_2$; $Q_{out} = h_4 - h_1$

## 5.3 STEAM TURBINE

Steam turbine is a prime mover, which converts heat energy of steam into mechanical energy by rotating motion of the blade. Total energy conversion involves two types of steam expansion—expansion of steam in nozzle and expansion of steam in turbine blades. The function of steam engine and steam turbine are similar, but steam engine converts the heat energy of steam into mechanical energy by reciprocating motion of the piston whereas in steam turbine the energy conversion takes place due to rotation of turbine shaft. Steam energy is used for low power generation and efficiency is lesser than that of steam turbine.

### 5.3.1 Classification of Steam Turbine

Broadly, steam turbine can be classified into two categories as follows:

1. Impulse turbine.
2. Impulse-reaction turbine.

Pure reaction turbine cannot be used for practical purpose; therefore, impulse-reaction turbine is referred as reaction turbine.

#### Impulse Turbine (de-Laval Turbine)

If torque produced on the shaft of the turbine is only due to change in momentum of steam and pressure of steam at inlet and outlet of the turbine being same, it is known as impulse turbine. In this turbine, the expansion of high-pressure steam occurs only in nozzle

During passage of steam through blade, its direction changes which results in change in momentum equal to impulse on blade.

#### Working of Impulse Turbine

In the impulse turbine, all the pressure drops occur in nozzle and there is no pressure drop of steam passing through blades. Let us consider steam enters the nozzle with pressure of $P_0$ and velocity of $V_0$, after expansion of steam in nozzle pressure drops to $P_1$ and velocity increases to $V_1$. High velocity jet of steam impinges on the blades with velocity $V_1$ gets deflected by an angle and comes out with smaller velocity $V_2$ producing an impulse on the blades. The pressure $P_1$ remains constant passing through the blades.

Now, momentum at the inlet of the blade – Momentum at the exit of the blade = Impulse on the blade absorbed in producing shaft work.

After expansion of steam in nozzle, it strikes the blades with absolute velocity $V_1$ which rotates the blade with mean peripheral velocity $u$, steam leaves the blade with relative velocity $V_{r2}$ and absolute velocity $V_2$ as shown in Figure 5.9.

$\alpha$ = Nozzle angle with direction of rotation of wheel
$\beta_1$ = Inlet blade angle
$\beta_2$ = Outlet blade angle
$u$ = Peripheral velocity of wheel

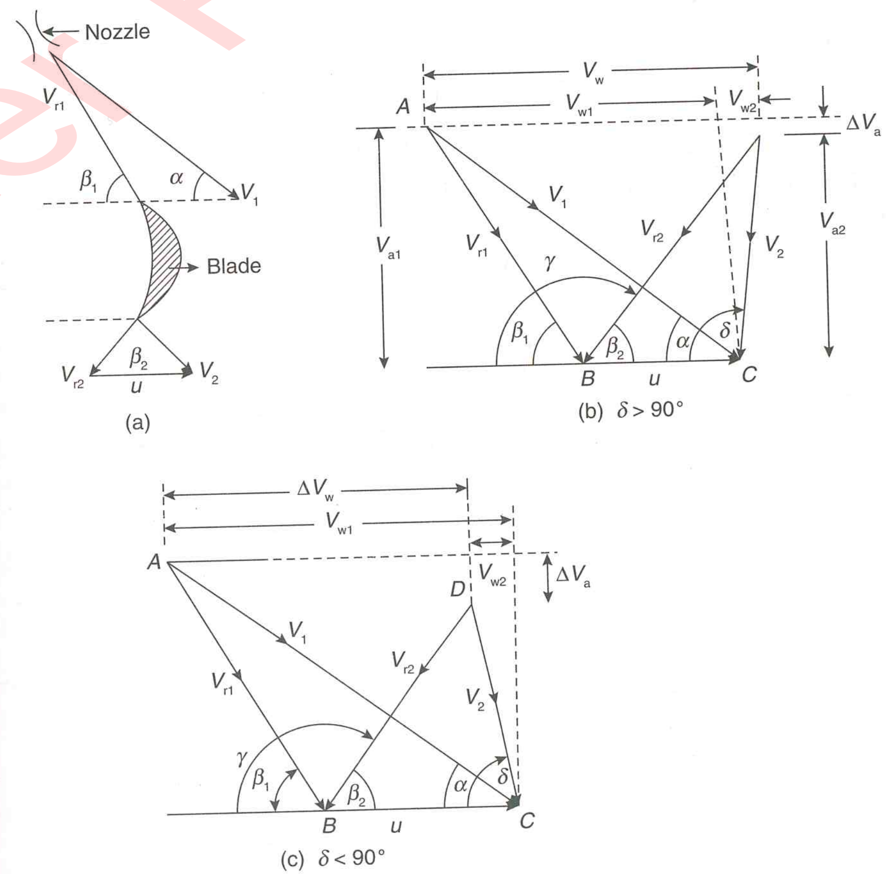



Figure 5.9 Velocity Diagram for Impulse Turbine

## 5.3.2 Compounding of Impulse Turbine

Single row of nozzle with single row of blade is called one stage of turbine. If steam at very high pressure is allowed to expand in single stage of turbine, the blade velocity will be too high. Such a high rotational speed cannot be used properly and also there will be velocity loss at the exit of the blade due to high exit velocity of steam. Therefore, to overcome these difficulties, the turbine is compounded or staged. In compounded turbines, steam is made to expand in number of stages instead of single stage and turbine speed is reduced which secures the same enthalpy drop of steam. There are three types of compounding of impulse turbine:

1. Pressure compounding or Reteau staging.
2. Velocity compounding or Curtis staging.
3. Pressure–velocity compounding.

### Pressure Compounding or Reteau Staging

Pressure compounding is splitting of whole pressure drop of steam from steam chest pressure to condenser pressure into series of small pressure drops across several stages of impulse turbine. The whole pressure drops occur in series of nozzles and there is no pressure drop in fixed blades as shown in Figure 5.11. The kinetic energy of steam increases in nozzles at the expense of the pressure drops and it is absorbed by the blades in producing torque on the shaft.

The pressure compounding of turbine is shown in Figure 5.11a and pressure–velocity diagram in Figure 5.11b. The enthalpy drop in one stage is equal to total enthalpy drop divided by number of stages as shown in Figure 5.11c.

### Velocity Compounding or Curtis Stages

In this compounding, whole pressure drop takes place in nozzle (only one row) and remains constant in fixed and moving blades. Velocity of steam remains constant in fixed blades and decreases in moving blades.

Figure 5.12a shows a two rows Curtis or velocity staging having two rows of moving blades and one row of fixed blade in between them. In three rows of Curtis stage, two row stages is followed by a second row of guide blade and third row of moving blade. Steam of high kinetic energy existing from nozzle impinges on first row of moving blades and gets deflected by the first row of fixed blades of guide blades. The steam after deflection from first row of fixed blades impinges on second row of moving blades and again gets deflected by second row of guide blades. Finally, steam impinges on third row of moving blades and thus, does work on turbine shaft.

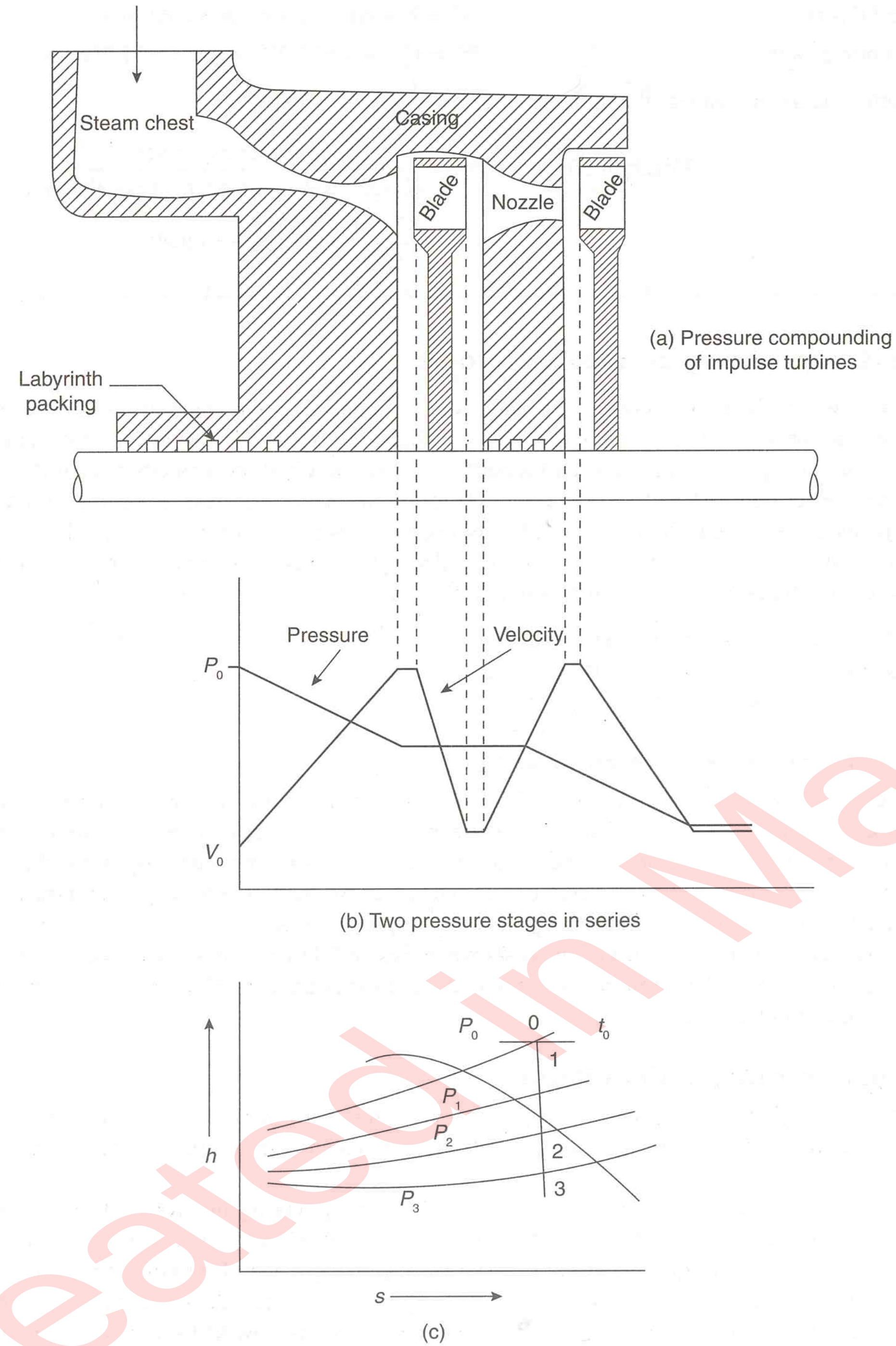



Figure 5.11 Pressure Compounding of Impulse Turbine

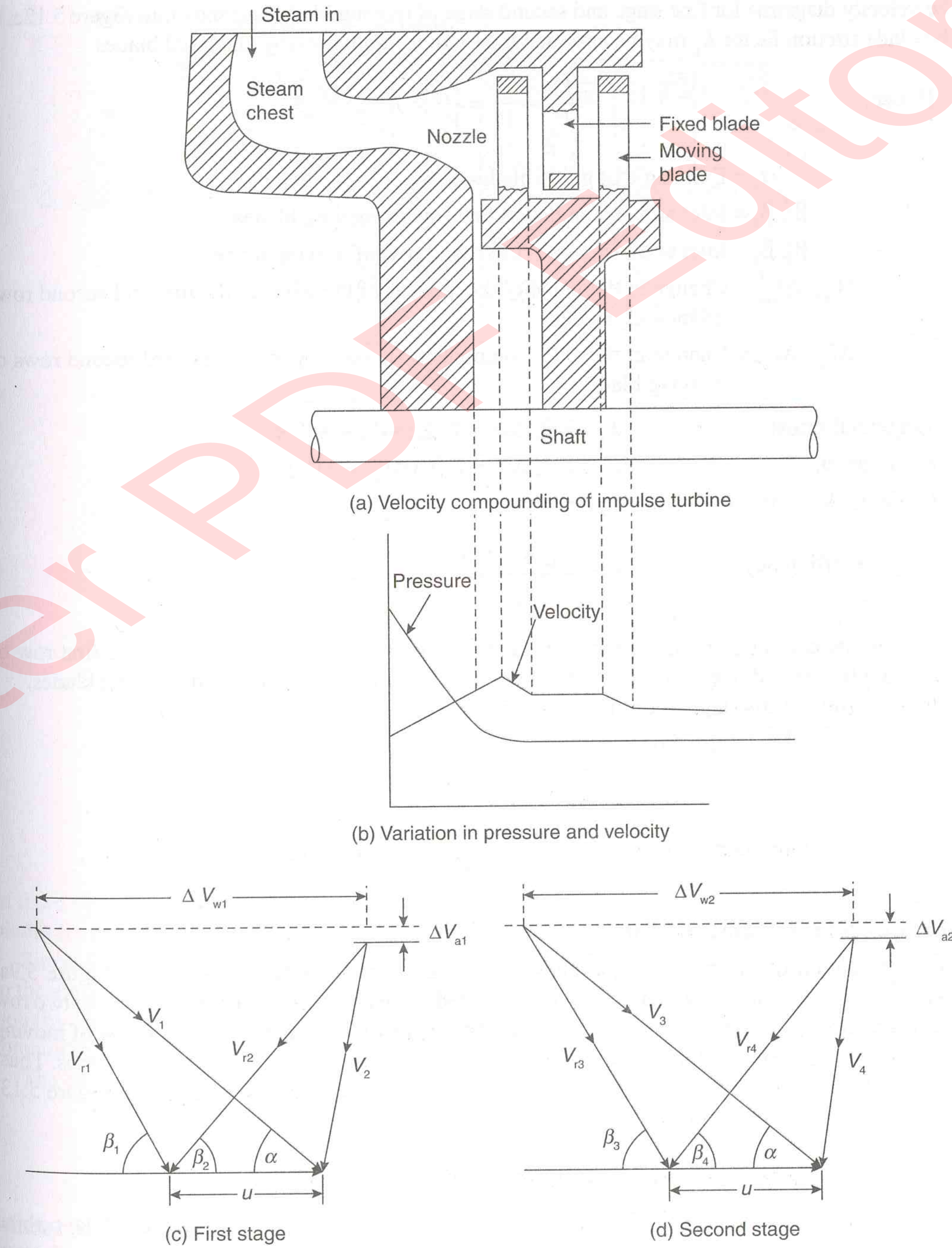


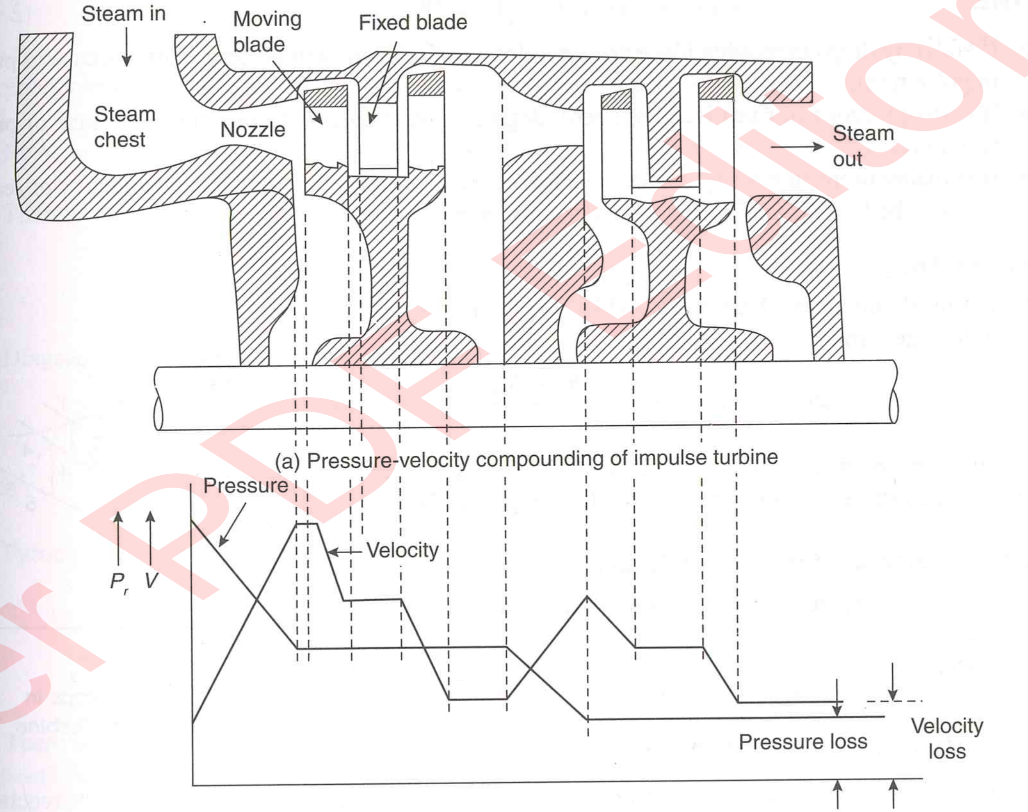

Figure 5.12 Velocity Compounding of Impulse Turbine

### Pressure–Velocity Compounding

It is combination of pressure compounding and velocity compounding as shown in Figure 5.9a. There are two rotors and only two rows of moving blades are attached on each rotor because two row wheels are more efficient than three row wheels. The steam on passing through each row of moving blades reduces its velocity, but pressure remains constant during passing through these blades. Thus, it acts as velocity compounded. The whole pressure drops in two nozzles as shown in Figure 5.13, thus it acts as pressure compounded.

## 5.3.3 Impulses-reaction Turbine (Reaction Turbine)

If steam expands both in nozzle as well as in blades of turbine, i.e., pressure at inlet of the turbine is more than that of outlet, it is known as impulse-reaction turbine. In this case, expansion of steam in nozzle creates impulse on blades and reaction due to minor expansion of steam during passing through moving blades. The small drop in pressure of steam in the moving blades gives back pressure to the moving blades in the direction opposite to the velocity. In this turbine there are stages




(a) Pressure-velocity compounding of impulse turbine

(b) Variation in pressure and velocity in pressure-velocity compounding

**Figure 5.13** Pressure–Velocity Compounding of Impulse Turbine

of fixed blades and moving blades; fixed blades act as nozzles that create an impact on the moving blades by reducing the pressure and increasing the velocity.

Since, the moving blade channels are also of nozzle shape. There is increase in kinetic energy due to the expansion of steam while flowing through the blade, that produces reaction in opposite direction (by Newton's third law of motion). Blades rotate due to both the impulse effect and the reaction force of steam jets. Such turbines are called impulse-reaction turbine or simply a reaction turbine.

The degree of reaction ($R$) of these turbines is defined as