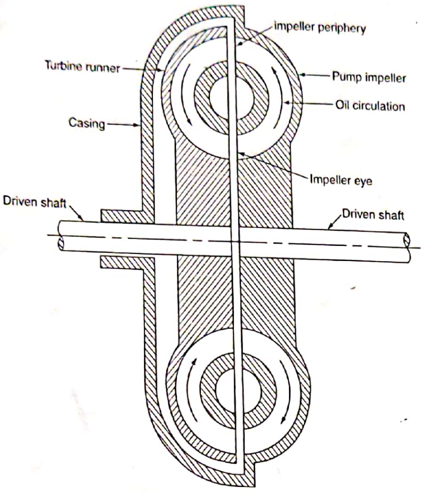


Figure 1 Fluid coupling.

involves unsteady operation, because torsional vibrations in either of the two halves of the coupling are not transmitted to the other.

8.2 Pump

A pump is a machine that imparts energy to a fluid so as to lift the fluid to a higher level, to transport the fluid from one place to another, to pressurize the liquid for some useful purpose or to circulate the liquid in a piping system. Pumps may be classified as shown in Figure 2.

Kinetic Energy Pump

In kinetic energy pumps, a velocity is imparted to the fluid. Most of this velocity head is then converted to pressure head. If the kinetic energy to a fluid is added by rotating it at high speed then it is called a ***centrifugal pump*** and if the kinetic energy provides an impulse in the direction of flow then it called an ***axial flow pump***.

1. **Centrifugal Pump:** The centrifugal pump works on the principle of conversion of the rotational kinetic energy into an increased static fluid pressure. The action is described by Bernoulli's principle. Centrifugal pumps are used for large discharge through smaller heads.

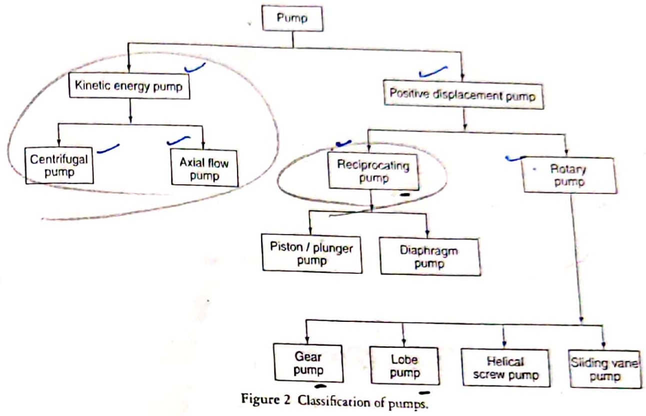


Figure 2 Classification of pumps.

Figure 3 shows the schematic diagram of a centrifugal pump. It consists of an impeller enclosed in a volute casing. The impeller is coupled with prime movers such as internal combustion engine or electric motor, which makes the impeller to rotate inside the volute casing. The rotation of the impeller imparts kinetic energy to the fluid forcing the fluid to move outward from the impeller vanes to the periphery. At the periphery, the change in area of the volute casing converts the fluid kinetic energy (velocity) into (static) pressure head. The increased pressure on the delivery side of the pump enables the fluid to flow or lift to a higher level. The low pressure created at the impeller eye (center) sucks the fluid from the suction pipe.

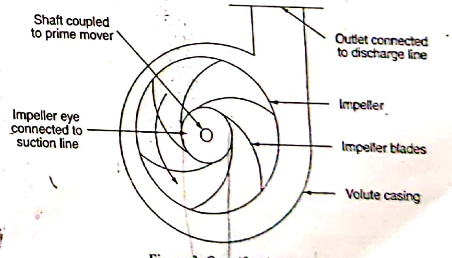


Figure 3 Centrifugal pump.

Scanned with CamScanner

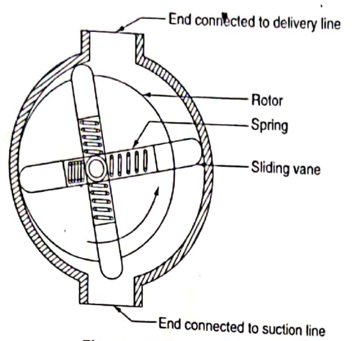


Figure 10 Sliding vane pump.

- **Sliding vane pump:** Figure 10 shows the schematic diagram of a sliding vane pump. The rotor is mounted off-center. Rectangular vanes are positioned at regular intervals around the curved surface of the rotor. Each vane is free to move in a slot. The centrifugal force from rotation throws the vanes outward to form a seal against the fixed casing. As the rotor revolves, a partial vacuum is created at the suction side of the pump, drawing in the fluid. This fluid is then transferred to the other side of the pump in the space between the rotor and the fixed casing. At the discharge side, the available volume is decreased and the resultant increase in pressure forces the fluid into the outlet line.

8.3 Compressors

A compressor is used to increase the pressure of the air which can be used for a variety of purposes, from industrial and manufacturing to commercial and personal purposes. The most well known use of the air compressor is in the case of pneumatic tools such as air-powered nail guns, staplers, sanders, spray guns, ratchet wrenches, etc. The working principle of compressor is similar to that of the pump. The main action of a pump is to transport the liquids because the liquids are relatively incompressible, whereas, the main action of the compressor is to increase the pressure and reduce the volume before transporting to some machine for useful purpose. Compressors may be classified as shown in Figure 11.

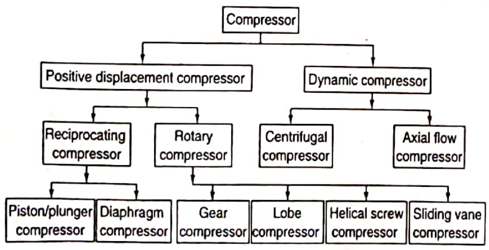


Figure 11 Classification of compressors.

Positive Displacement Compressor

A positive displacement compressor causes a fluid to move by trapping a fixed amount of it, then compressing to a designed pressure and finally discharging to the storage tank. Positive displacement compressors can be classified as reciprocating-type and rotary-type.

1. **Reciprocating-Type Compressor:** In a reciprocating-type compressor, a volume of air is drawn into the cylinder, compressed to a designed pressure and finally discharged to a storage tank. The discharge from the compressor is pulsating, so a storage tank is used to provide a more even flow.
   - **Piston compressor:** Figure 12 shows the schematic diagram of reciprocating piston compressor. It consists of a piston moving to and fro in the cylinder. The piston is driven by a slider-crank mechanism, powered by the prime mover such as an electric motor. When piston moves away from the valve end of the cylinder, the pressure in the cylinder is reduced below the atmospheric pressure. This causes the non-return-type suction valve to open and suck the air from the atmosphere. The suction of the air continues until the piston reaches its outermost position in the cylinder.

     Now the crank pushes the piston towards the valve end of the cylinder. This causes suction valve to close and air to attain a high pressure for which the compressor is designed. When the pressure in the cylinder rises to the designed pressure, the delivery valve opens. The air at high pressure discharges to the storage tank until the piston reaches its innermost position in the cylinder.
   - **Diaphragm compressors:** They work in a pattern similar to that of piston compressor. Diaphragm compressor eliminates disadvantages of piston compressor by replacing the piston with a flexible diaphragm. These compressors are used for compressing hydrogen and natural gas in addition to a number of other applications.
2. **Rotary Compressors:** Rotary compressors operate on the principle that a rotating gear, screw, vane, etc. traps the air in the suction side of the pump casing and forces it to the discharge side of the casing. Their working principle is similar to that of the rotary pumps.

Dynamic Compressor

In a dynamic compressor, velocity is imparted to the air. Most of this velocity head is then converted to pressure head. If the kinetic energy to air is added by rotating it at high speed, it is called a *centrifugal compressor* and if the kinetic energy provides an impulse in the direction of flow, it is called an *axial flow compressor*.

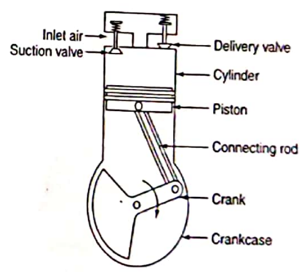


Figure 12 Piston compressor.

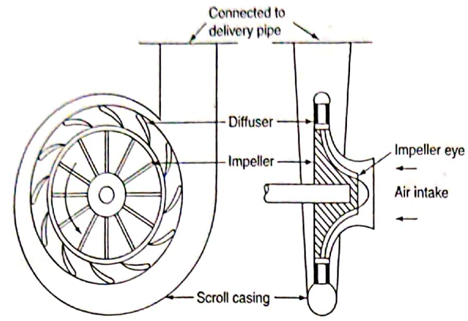


Figure 13 Centrifugal compressor.

1. Centrifugal Compressor: They work on the principle of conversion of the rotational kinetic energy into an increased static fluid pressure. They are used throughout the industry because they have fewer rubbing parts, are relatively energy efficient and have higher airflow than a similarly sized reciprocating compressor. Centrifugal compressors are also used in gas turbine engines. In internal combustion engines centrifugal compressors are used as superchargers and turbochargers.

   Figure 13 shows the schematic diagram of a centrifugal compressor. It consists of an impeller and a diffuser enclosed in a scroll casing. The impeller is coupled with an internal combustion engine or an electric motor which makes the impeller to rotate inside the volute casing. Owing to the rotation of the impeller, a low pressure is created at the impeller eye (center) which sucks the air into the impeller. The impeller imparts kinetic energy to the air forcing the fluid to move to the periphery into the diffuser. At the diffuser, owing to increase in cross-sectional area the velocity of air is reduced. The diffuser guides the air and converts a part of the kinetic energy into pressure energy. The air from the diffuser enters into the scroll casing where the remaining kinetic energy is converted into static pressure energy. The high pressure air is discharged through the outlet.

2. Axial-Flow Compressor: An axial-flow compressor is a dynamic rotating compressor that uses arrays of fan-like aerofoils to progressively compress the air. It produces a continuous flow of compressed gas and has the benefit of high efficiencies and large mass flow capacity. Axial-flow compressors are widely used in gas turbines, such as jet engines, high-speed ship engines and small-scale power stations. They are also used in industrial applications such as large volume air separation plants, blast furnace air, fluid catalytic cracking air and propane dehydrogenation.

   Figure 14 shows a schematic diagram of an axial-flow compressor. It consists of a central drum called rotor having a number of rows of annular aerofoil blades attached. These blades rotate between a similar number of rows of stationary aerofoil blades attached to a stationary tubular casing called stators. A pair of rotating aerofoil and stationary aerofoil is called a stage. The rotor is coupled with the prime movers. When the rotor rotates, it imparts kinetic energy to the air and the stator converts the increased kinetic energy into static pressure through diffusion. The cross-sectional area between rotor drum and tubular casing is reduced in the flow direction to maintain axial velocity when the fluid is compressed.

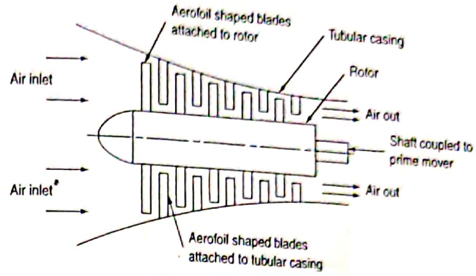


Figure 14 Axial-flow compressor.

8.4 Hydraulic Turbine

A hydraulic turbine is a rotary engine used for electric power generation. It takes energy from flowing water and converts it into mechanical energy. It is used in hydraulic power plants. The hydraulic turbines can be classified as follows:

1. On the basis of action of water on the runners as
   - **Impulse Turbine:** There is no pressure drop on the runners. Kinetic energy of water coming from the jet is used to run the runner. Example: Pelton turbine.
   - **Reaction Turbine:** There is a loss of kinetic energy as well as pressure on the runners of the blade. Example: Francis turbine, Kaplan turbine.
2. On the basis of direction of flow of water in the runner as
   - **Tangential-Flow Turbine:** In tangential-flow turbine, water strikes the runner tangential to the path of rotation. Example: Pelton turbine.
   - **Radial-Flow Turbine:** In radial-flow turbine, water enters the runner radially and comes out axially. Example: Francis turbine.
   - **Axial-Flow Turbine:** In axial-flow turbine, water flows parallel to the axis of the turbine. Example: Kaplan turbine.
3. On the basis of available head at the inlet of the turbine as
   - **High-Head Turbine:** The turbine is capable of working under high potential head of water, above 250 m. Example: Pelton turbine.
   - **Medium-Head Turbine:** The turbine is capable of working under medium range of potential head, about 60 m to 250 m. Example: Francis turbine.
   - **Low-Head Turbine:** The turbine is capable of working under low potential head of water, less than 60 m. Example Kaplan turbine.
4. On the basis of specific speed (specific speed is defined as the speed of a geometrically similar turbine that would develop 1 kW under 1 m head) as
   - **Low Specific Speed:** The turbine works in the range of 10 and 50. Example: Pelton turbine.
   - **Medium Specific Speed:** The turbine works in the range of 50 and 350. Example: Francis turbine.
   - **High Specific Speed:** The turbine works in the range of 250 and 850. Example Kaplan turbine.

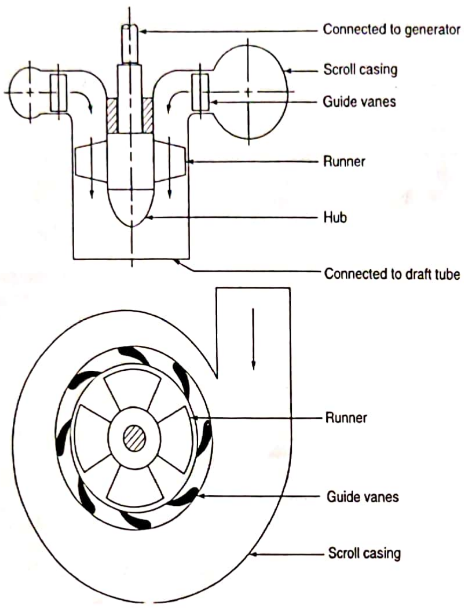


Figure 17 Kaplan turbine.

Figure 17 shows an arrangement of a Kaplan turbine. It is also located between the high pressure water source and the low pressure water exit. The inlet is through scroll casing which is in the form of spiral. This ensures constant velocity of water flow along the path. After entering into the casing, water gets distributed into the guide blades. From the guide vanes, water turns through a right angle and flows in the axial direction. Water then passes through the runner blades. This axial flow of water acting on the runner vanes causes the runner to rotate. Finally, water is discharged to the tail race through a gradually expanding tube called the draft tube.

8.5 Hydraulic Power Plant

Hydraulic power plants are based on renewable source of energy for generating electricity. It does not produce waste or carbon dioxide, and thus do not contribute to greenhouse gases. Hydraulic power plants supply about 715 GW of electricity which is 20% of the world electrical power.

Rain falling over the earth's surface has potential energy relative to ocean towards it flows. If at a certain site the water falls through an appreciable vertical height, its potential energy can be can be converted into the mechanical energy by flowing water through hydraulic turbines. The power developed can be calculated as:

$$\text{Power} = \frac{\rho g H Q}{1000} \times \eta_h \times \eta_m \times \eta_e$$

where ρ is the density of water, g is the acceleration due to gravity, H is the difference in height between the source and water's outflow called the head, Q is the rate of water flow, η_h, η_m, η_e are the hydraulic, mechanical and generator efficiencies, respectively.

On the basis of quantity of water available hydraulic power plants can be classified as

1. run-of-the-river plants;
2. storage-type plants;
3. pumped storage plants.

Run-of-the-River Plants

They are built on the rivers having a consistent and steady flow. They use the natural flow of water and elevation drop of a river to generate electricity. Power stations of this type do not have reservoir capacity. The output is highly dependent on natural run-off. Spring melts will create a lot of energy while dry seasons will create relatively little energy. If a site with consistent flow is chosen this disadvantage is negated. As India has majorly dry days in a year such plants are not suitable.

Storage-Type Hydraulic Plants

Storage-type hydraulic plants are usually *base load plants*. Such plants are useful where there is a great seasonal fluctuation. It has a large reservoir which stores the excess water during the flood days to use it to operate the plant during dry season.

Figure 18 shows the arrangement of a storage-type hydraulic power plant. A dam is constructed across a river which acts as an artificial storage reservoir. The water is stored at higher elevation and thus

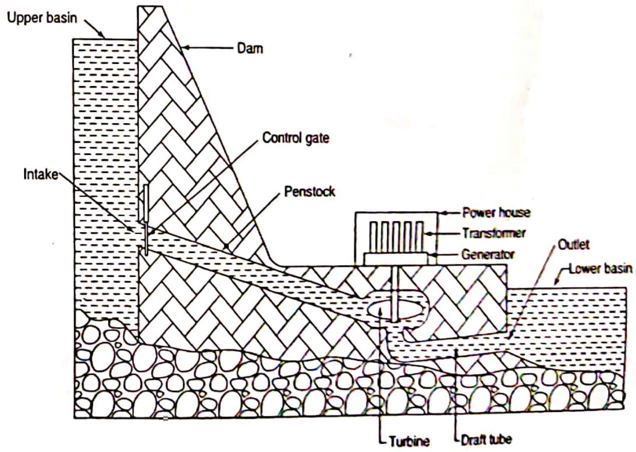


Figure 18 Storage-type hydraulic power plants.

has the potential to do work. The control gate is built on the side of the dam. When the control gate is opened, the water from the reservoir goes through the intake towards the turbines through the penstock.

Spillway (not shown in the figure) is constructed to act as a safety valve. It discharges the overflow water to the down stream side when the reservoir is full. The penstock is a long tube that carries the water towards the turbines. The force of the water is used to turn the turbines. The work that is done by the water to turn the turbines is mechanical energy.

The generators comprise four basic components: the shaft, the exciter, the rotor and the stator. The turning of the turbines powers the exciter to send an electrical current to the rotor. The rotor is a series of large electromagnets that spin inside a tightly wound coil of copper wire, called the stator. A voltage is induced in the moving conductors by an effect called *electromagnetic induction*. The electromagnetic induction induced by the spinning electromagnets inside the wires causes electrons to move, creating electricity.

Now, the water coming out of the turbines flows through pipelines called draft tubes and flows back to the river.

Pumped Storage Plants

Pumped storage plants are usually peak *load plants*. They are used to meet the excess electric demand which cannot be fulfilled by the base load power plants. They act as the energy storage systems. Usually reversible pump-turbine unit and reversible motor-generator units are used.

A pumped storage plant consists of a tail water reservoir and a head water reservoir at different elevations as shown in Figure 19. The generating pumping plant is at the lower end. During times of peak load (high electricity demand), pumped storage plant produces electricity by moving water from the

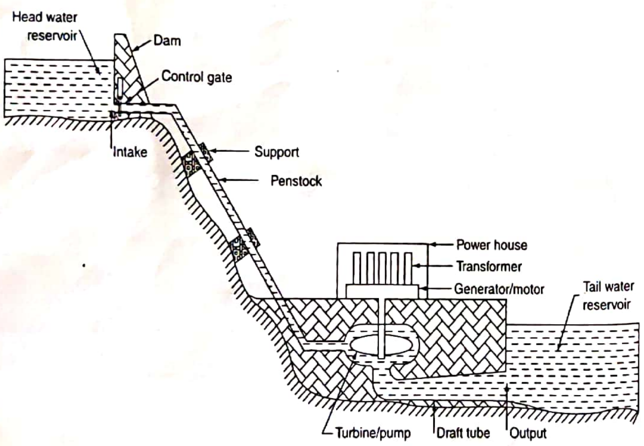


Figure 19 Pumped storage plants.

head water reservoir to the tail water reservoir. At times off-peak hours (low electricity demand), the surplus electrical energy generated by the base load plants is utilized to pump water from tail water reservoir into the head water reservoir. Thus, the hydraulic energy is restored. It can be seen that the turbine-generator unit which is used to develop power during peak load is used as pump-motor unit during off-peak hours.

The pumped storage plants generally use Francis turbines which may have either vertical or horizontal shaft. Taking into account evaporation losses from the exposed water surface and conversion losses, approximately 70–85% of the electrical energy used to pump the water into the elevated reservoir can be regained. The technique is currently the most cost-effective means of storing large amounts of electrical energy on an operating basis, but capital costs and the presence of appropriate geography are critical decision factors.

The system is economical because it flattens out load variations on the power grid, permitting thermal power stations such as coal-fired plants and nuclear power plants that provide base-load electricity to continue operating at peak efficiency, while reducing the need for "peaking" power plants that use costly fuels.

8.6 Pneumatic Machines

Pneumatic machines are basically the machine tools driven by compressed air, supplied from the storage tank of an air compressor. They have higher power to weight ratio allowing a smaller and lighter tool to accomplish the task. They are usually cheaper and safer to run and maintain in comparison to their electric power tool counterparts.

Pneumatic Components

To operate a pneumatic machine it is mandatory to supply properly conditioned air in sufficient volume at correct pressure. The basic components used before the air enters the pneumatic machines are as follows:

1. Compressor: The supply of air starts from the compressor. It sucks the atmospheric air and stores it in the receiver tank. The compressors have mostly rated output pressure in Pascal and rated volume in cubic meter per second. This is often known as *free air delivered* (FAD). Figures 20(a) and (b) show symbols for a compressor and a receiver, respectively.
2. Filter: Air from the compressor contains dust from the ambient atmosphere, condensed water and oil sludge that bypass the compressor rings. These by-products of compressing and transmitting air must be removed to keep moving parts of the machine working properly. A filter

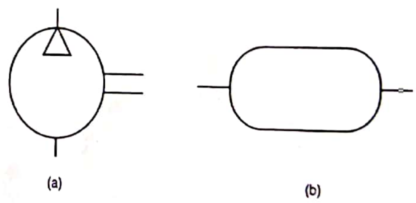


Figure 20 Symbols: (a) Single-stage compressor; (b) air receiver.

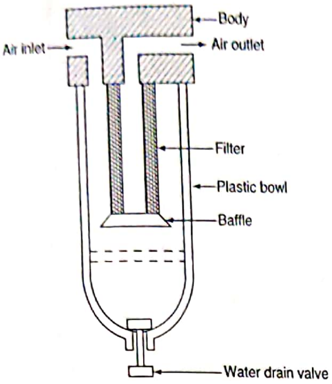
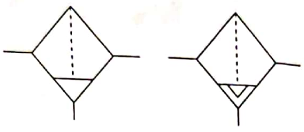


Figure 21 Simple air filter.



(a) (b)

Figure 22 Symbols used to represent an air filter: (a) Manually drained type; (b) automatically drained type.

cleans the air and separates condensed water. Figure 21 shows the schematic diagram of a simple air filter. Air entering the filter is channelled into the bowl with a downward circular motion. The centrifugal force of this swirling action slings water droplets outward. The water falls and collects below the baffle at bottom of the bowl called *quiet zone*. From the quite zone, water is drained either manually or automatically. The air then flows through a porous filter element where dust particles of size generally larger than 40 micron are removed. The filtered air moves out from the outlet.

Figures 22 (a) and (b) show the symbols used for both manually or automatically water drained air filters, respectively. A coalescing filter may also be used if it is required to have water droplets, dust particles as small as 0.3–0.6 micron along with oil vapors.

3. Pressure Regulator: A pressure regulator is used to maintain the air supply to a pneumatic machine at the rated pressure, regardless of variations in flow and upstream pressure. Thus it extends the life of a pneumatic machine and increases its operating efficiency.

   Figure 23(a) shows the schematic diagram of an unbalanced poppet regulator. Figure 23(b) shows the symbolic representation. Rotating the handle in a direction compresses the adjustment spring which in turn forces the diaphragm to move downward. The diaphragm pushes the stem down and the poppet uncovers the orifice. The air enters the regulator at the supply pressure, passes through the orifice and moves out at the rated pressure. As the downstream pressure rises at the outlet, the air exerts higher pressure at the underside of the diaphragm. The seam moves up and reduces the opening between the orifice and the poppet which results to maintain the desired pressure. Again as soon as downstream pressure demand varies, the regulator automatically repositions the poppet in relation to the orifice and maintains the desired pressure.

4. Air Lubricator: Almost all pneumatic machines perform better when properly lubricated with oil. Too little oil can allow excessive wear and cause premature failure. Excessive oil is wasteful.

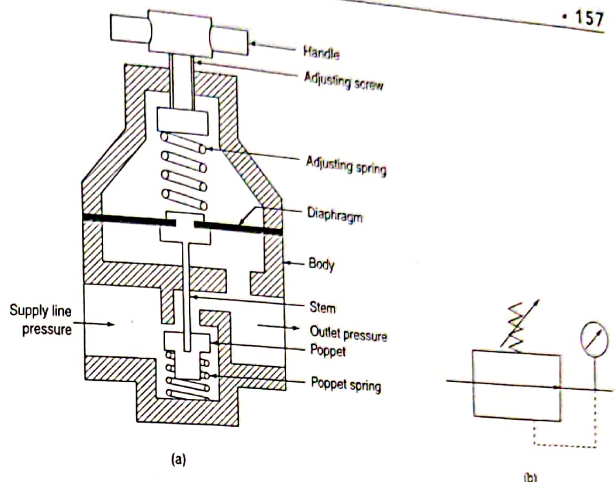


Figure 23 Unbalanced poppet regulator: (a) Schematic diagram; (b) symbolic representation.

Intermittent lubrication may be the worst condition of all because the oil film can dry out and form sludge or varnish on the internal surfaces of the equipment. An air lubricator is used to inject oil mist into the air stream in the desired amount to lubricate valves, cylinders and air motors continuously.

Figure 24(a) shows the schematic diagram of an air lubricator and Figure 24(b) shows the symbolic representation. When the air passes through the venturi, it sucks the oil up and then, through a capillary, drips it into the air stream. The moving air breaks up the oil into a mist or fog and carried downstream. Under low-flow conditions all of the air passes through the venturi. During higher flow conditions, a spring-loaded bypass valve opens to direct the excess flow around the venturi to a point downstream where it rejoins the lubricated flow. A manual adjusting valve sets the oil drip-rate and a sight glass enables the operator to monitor the output. A fill plug provides access to refill the reservoir.

The combination of filter, regulator and lubricator is commonly denoted as FRL. Figure 25(a) shows how the symbols appear when their individual symbolic representation is combined together in a sequence. However, the FRL may also be represented by the symbol as shown in Figure 25(b).

5. Cylinders: Pneumatic cylinder converts air pressure into straight rectilinear motion to run the mechanical system. Cylinders on the basis of applications can be classified as light, medium and heavy duty. On the basis of function these can be classified as single acting and double acting.

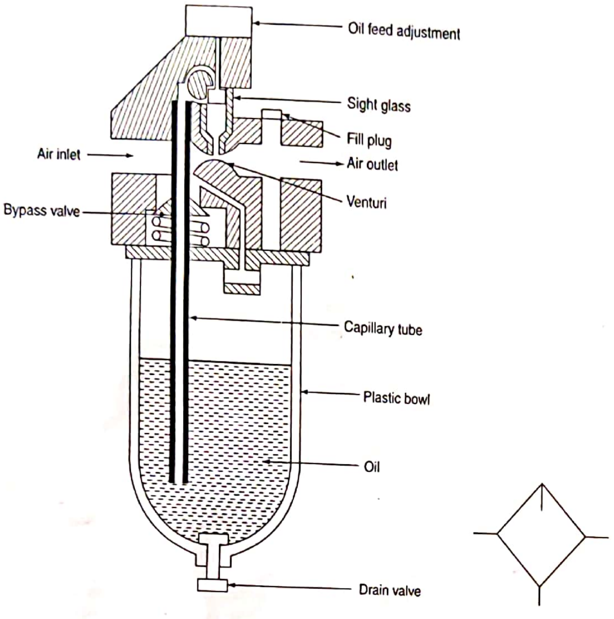


Figure 24 Air lubricator: (a) Schematic diagram; (b) symbolic representation.

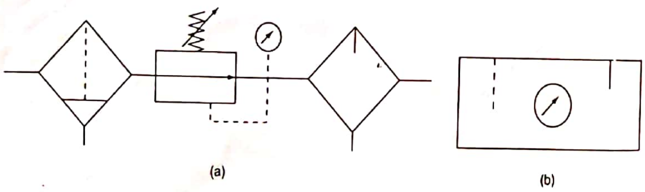


Figure 25 Symbolic representation of combined filter, regulator and lubricator (FRL) system: (a) Actual; (b) simplified.

- **Single-acting cylinder:** In a single-acting cylinder, the compressed air is fed from one side of the piston. Hence, the cylinder produces work in one direction only. A helical spring is used to return the piston to its original position with sufficiently high speed.

(Swept Vol)

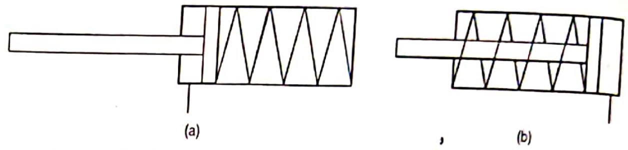


Figure 26 Symbol for single-acting cylinder: (a) Working during forward/inward stroke; (b) Working during return/outward stroke.

Figure 26(a) shows a single-acting cylinder in which forward motion is imparted by the air and the return motion is imparted by the spring. Figure 26(b) shows a single-acting cylinder in which forward motion is imparted by the spring and the return motion by the air.

- **Double-acting cylinder:** In a double-acting cylinder, the compressed air is fed alternately from both sides of the piston. Hence the cylinder produces work during both advance and return strokes. Figure 27 shows the symbolic representation of a double-acting cylinder.

6. **Directional Control Valve:** A directional control valve is used to control and regulate the air supply to the cylinder so as to generate the desired level of pneumatic energy. Depending upon the port opening and valve positions, the directional control valves may be classified as 2/2, 3/2, 4/2, 4/3, etc.

   Figures 28 and 29 show two types of two-way, two-position valves. In Figure 28, the air entering through one port will flow out of the other port when the valve is closed, whereas in Figure 29, the air entering through one port will not flow out of the other port unless the valve is opened/actuated.

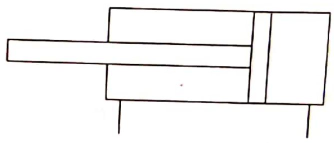


Figure 27 Symbol for double-acting cylinder.

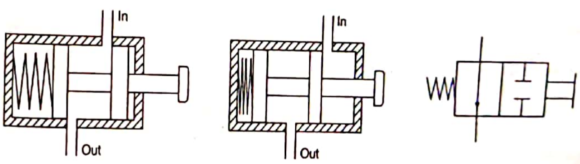


Figure 28 Two/two directional control valve remains normally open: (a) Inactivated; (b) actuated; (c) symbol.

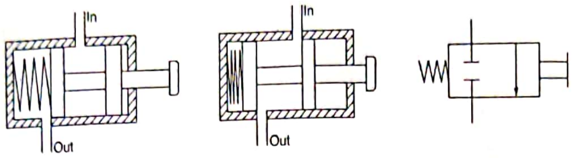


Figure 29 Two/two directional control valve remains normally closed: (a) Inactivated; (b) actuated; (c) symbol.

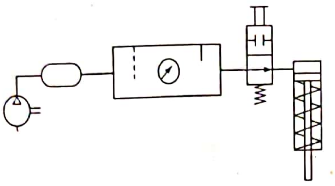


Figure 30 Use of pneumatic machine for pneumatic reverting and pneumatic hammering.

Applications

The conversion of air pressure into rectilinear motion of the piston rod (connected to the piston) can be used to run a large number of machines called pneumatic machines. Figure 30 shows a typical symbolic sketch of the system where reciprocating motion of the piston rod can be used for reverting and hammering purpose. Similarly, pneumatic machines find application as air impact wrench, air ratchet, airbrush, pneumatic grinder, pneumatic sander, pneumatic drill, pneumatic screwdriver, pneumatic tapping machine, pneumatic hammer, pneumatic hacksaw, pneumatic trimmer, pneumatic paint gun, pneumatic polisher, pneumatic nail gun and pneumatic paint sprayer.

Points to Remember

1. Fluid coupling is used to transmit rotating power from a driving shaft to a driven shaft with the help of fluid.
2. In a centrifugal pump the kinetic energy is added to the fluid by rotating the impeller at high speed. The kinetic energy of the fluid is converted into pressure energy in the volute casing which helps in raising the fluid to a higher altitude.
3. In an axial-flow pump, the kinetic energy provides an impulse to the fluid in the direction of fluid flow.
4. In a positive displacement pump, the fluid is transported by trapping a fixed amount of it and then displacing that trapped volume into the discharge pipe.
5. A compressor is used to increase the pressure of the air.
6. Pelton turbine is a tangential-flow impulse-type hydraulic turbine.
7. Francis turbine is a radial-flow or mixed-flow-type reaction turbine.
8. Propeller and Kaplan turbines are axial-flow-type reaction turbines.

9. Run-of-the-river hydraulic plants are built on the rivers with a consistent and steady flow.
10. Storage-type hydraulic plants are usually base load plants.
11. Pumped storage plants are usually peak load plants. They act as the energy storage system.

Key Terms

Fluid coupling	Sliding vane pump	Radial-flow turbine
Centrifugal pump	Reciprocating compressor	Axial-flow turbine
Axial-flow pump	Centrifugal compressor	Pelton wheel
Piston pump	Axial-flow compressor	Francis turbine
Diaphragm pump	Rotary compressor	Kaplan turbine
Gear pump	Impulse turbine	Run-of-the-river hydraulic plant
Lobe pump	Reaction turbine	Storage-type hydraulic plant
Helical screw pump	Tangential-flow turbine	Pumped storage hydraulic plant

Objective-Type Questions

Multiple-Choice Questions

1. Which of the following device is used to transmit rotating power?
   a. Fluid coupling
   b. Dynamometer
   c. Hydraulic turbine
   d. Pump
2. Pumps are used to
   a. lift fluid to a higher level
   b. transport the fluid from one place to another
   c. pressurize the fluid for some useful work
   d. all of these
3. Which of the following is a reciprocating pump?
   a. Diaphragm pump
   b. Axial-flow pump
   c. Sliding vane pump
   d. All of these
4. In a centrifugal pump, the volute casing helps in converting
   a. mechanical energy into kinetic energy
   b. kinetic energy into pressure head
   c. pressure head into kinetic energy
   d. kinetic energy into mechanical energy
5. Which of the following is a dynamic-type compressor?
   a. Reciprocating piston compressor
   b. Axial-flow compressor
   c. Helical screw compressor
   d. Sliding vane compressor
6. The specific speed of Pelton wheel is in the range of
   a. 10–50
   b. 50–350
   c. 250–850
   d. 10–850
7. Francis turbines are used for a potential head in the range of
   a. 5–60 m
   b. 60–250 m
   c. 250–650 m
   d. 650–1250 m

9 Laws of Thermodynamics

LEARNING OBJECTIVES

After completing this chapter, you will learn:

- Joule apparatus and mechanical equivalent
- First law of thermodynamics
- The Kelvin–Planck statement for second law of thermodynamics
- Clausius statement for second law of thermodynamics
- Reason for considering both Kelvin–Planck and Clausius statements as second law of thermodynamics

Thermodynamics is the study of the effects of changes in temperature, pressure and volume on physical systems at the macroscopic scale by analyzing the collective motion of their particles. Roughly, heat means "energy in transit" and dynamics relates to "movement". Thus in essence, thermodynamics deals with the movement of energy. The starting point for most thermodynamic considerations is the laws of thermodynamics, which postulate that energy can be exchanged between physical systems as heat or work.

9.1 Joule Apparatus and Mechanical Equivalent

Energy that enters a system as heat may leave the system as work or energy that enters the system as work may leave the system as heat. In 1843 Joule independently discovered this mechanical equivalent in a series of experiments.

He considered an insulated vessel as a closed system, shown in Figure 1(a). It was filled with known mass of water and a paddle wheel. The paddle immersed in water was made to rotate by a descending weight attached to a string. The quantity of work was measured by the potential energy lost by the weight in descending (work done = mgz). Now the insulation is removed and the vessel is placed in a bath, as shown in Figure 1(b), to cool back to initial temperature. The energy involved in increasing the temperature of the bath was shown equal to that supplied by the lowered weight.

Mathematically,

$$\oint dW = \oint dQ$$

Although heat and work are represented in the same units (as Joule) but they are different forms of energy. This experiment shows that the algebraic sum of work and heat interaction during a cycle is zero. The first law of thermodynamics is based on the Joule experiment.

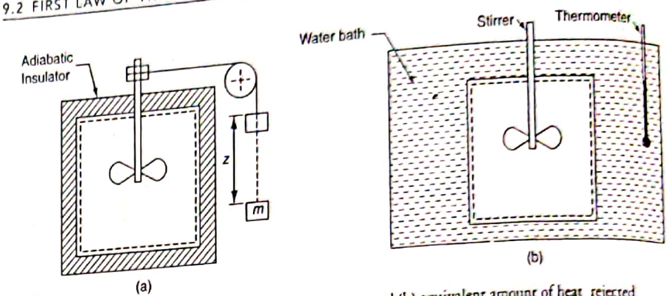


Figure 1 (a) Work supplied using potential energy and (b) equivalent amount of heat rejected

9.2 First Law of Thermodynamics

The first law of thermodynamics states that *"during any cycle a system undergoes, the cyclic integral of the heat is proportional to the cyclic integral of the work"*.

Mathematically,

$$\oint dQ = \oint dW$$

The first law of thermodynamics cannot be proved analytically, but experimental evidence has repeatedly confirmed its validity. Since no violation has ever been demonstrated, the law is accepted as a general law of nature.

Problem 1

A system undergoes a cycle comprising four processes. The heat transfers in each process are: $Q_{ab} = 720$ kJ, $Q_{bc} = -80$ kJ, $Q_{cd} = 40$ kJ and $Q_{da} = -640$ kJ. The respective work transfers are $W_{ab} = -90$ kJ, $W_{bc} = -50$ kJ, $W_{cd} = 130$ kJ. Determine the work interaction during the process d–a.

Solution: Given $Q_{ab} = 720$ kJ, $Q_{bc} = -80$ kJ, $Q_{cd} = 40$ kJ, $Q_{da} = -640$ kJ, $W_{ab} = -90$ kJ, $W_{bc} = -50$ kJ, $W_{cd} = 130$ kJ.

From the first law of thermodynamics, for the closed system undergoing a cycle,

$$\oint dQ = \oint dW$$

or

$$Q_{ab} + Q_{bc} + Q_{cd} + Q_{da} = W_{ab} + W_{bc} + W_{cd} + W_{da}$$

$$720 - 80 + 40 - 640 = -90 - 50 + 130 + W_{da}$$

$$W_{da} = 50\,\text{kJ}$$

Problem 2

The cylinder containing the air comprises compression and expansion strokes in the cycle. During the compression stroke work done by the piston is 9200 Nm and heat rejected to the surroundings is 50 kJ. During expansion stroke work done by the air on the piston is 8400 Nm. Determine the quantity of heat transferred to or from the system.

Solution: Given $W_1 = -9200$ N-m $= -9.2$ kJ, $Q_1 = -50$ kJ, $W_2 = 8400$ Nm $= 8.4$ kJ.
From the first law of thermodynamics, for the closed system undergoing a cycle,

$$\oint dQ = \oint dW$$

$$Q_1 + Q_2 = W_1 + W_2$$
$$-50 + Q_2 = -9.2 + 8.4$$
$$Q_2 = 50.8 \text{ kJ}$$

The positive sign indicates that the heat is transferred to the system. Thus, heat transferred to the system is 50.8 kJ.

Problem 3

During one cycle the working fluid in an engine engages in two work interactions – 20 kJ to the fluid and 42 kJ from the fluid – and three heat interactions – two of which are 85 kJ to the fluid and 50 kJ from the fluid. Calculate the magnitude and direction of the third heat interaction.

Solution: Given $W_1 = -20$ kJ, $W_2 = 42$ kJ, $Q_1 = 85$ kJ, $Q_2 = 85$ kJ, $Q_3 = -50$ kJ.
From the first law of thermodynamics, for the closed system undergoing a cycle,

$$\oint dQ = \oint dW$$

$$Q_1 + Q_2 + Q_3 = W_1 + W_2 + W_3$$
$$85 + 85 - 50 = -20 + 42 + W_3$$
$$W_3 = 98 \text{ kJ}$$

First Law of Thermodynamics for a Closed System Undergoing a Change of State

The first law of thermodynamics follows that if a system is taken through a cycle of processes so that it returns to the same state of condition from which it started the sum of heat and work effects will be zero. Suppose a system represented by state point 1 undergoes a process 1–a–2 and comes back to initial state following the path 2–b–1 as shown in Figure 2. On reaching the initial state all properties of the system are restored. From the first law of thermodynamics when the system is undergoing the cyclic process, the relation between heat and work may be written as

$$Q_1 - Q_2 = W_1 - W_2$$

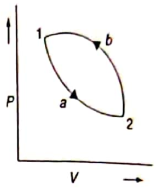


Figure 2 P–V diagram for a system undergoes a cycle.

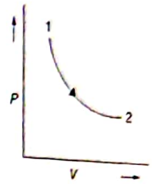


Figure 3 P–V diagram for a system undergoes a process.

Now we consider the first law of thermodynamics for control mass that undergoes a change of state as shown in Figure 3. If a system undergoes a change of state during which both heat transfer and work transfer are involved, the net energy transfer will be stored or accumulated within the system. If Q is the amount of heat transferred to the system and W is the amount of work transferred from the system during the process, the net energy transfer $Q - W$ will be the stored in the system. Therefore,

$$Q - W = \Delta E$$
$$Q = \Delta E + W$$

where ΔE is the increase in the energy of the system. Here Q, W and ΔE are expressed in the same units (in Joules). If the electric, magnetic and chemical energies are absent and changes in potential and kinetic energy for a closed system are neglected, the above equation can be written as

$$Q = \Delta U + W$$

where ΔU is the increase in the internal energy of the system.

It may be noted that *heat added to the system will be considered as positive and the heat rejected from the system as negative. Work done by the system will be considered as positive and the work done on the system as negative.*

Corollaries of First Law of Thermodynamics

The first law of thermodynamics has a number of important consequences which are standardized in the form of corollaries.

1. First Law for a Process: *There exists a property of a closed system such that a change in its value during any change of state is given by the difference between the heat supplied and work done.*

$$\Delta E = Q - W$$

   The property E is called energy of the system. This energy resides within the system and increases or decreases with change of state.
2. First Law for an Isolated System: *The energy of an isolated system is always constant.* For an isolated system there is no interaction of the system with the surroundings. So both heat and work interactions are absent, that is, $Q = 0$ and $W = 0$. Therefore, the first law of thermodynamics gives

$$\Delta E = 0 \text{ or } E = \text{constant}$$

   This fact is often referred to as the principle of conservation of energy and can be stated as "energy than neither be created nor be destroyed but can be converted from one form to another".

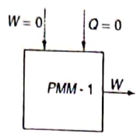


Figure 4 PMM-1.

3. **Perpetual Motion Machine of First Kind (PMM-1):** *A perpetual motion machine of first kind is impossible.* A perpetual motion machine of first kind is an imaginary device which delivers work continuously without any input as shown in Figure 4. Thus the interaction of the system with the surrounding is the delivery of work. Such a device delivers energy from nothing and violates the first law of thermodynamics.

As $\oint dQ$ is zero the value of $\oint dW$ must also be zero.

Problem 4

A non-flow process loses 2100 kJ of heat and gains 420 kJ of internal energy. How much work is done and is the process a compression or an expansion?

Solution: Given $Q = -2100$ kJ, $\Delta U = 420$ kJ.
From the first law of thermodynamics, for the closed system undergoing a process,

$$Q = \Delta U + W$$
$$-2100 = 420 + W$$
$$W = -2520 \text{ kJ}$$

The negative sign indicates work done is done on the system and it is a compression process. The amount of work done on the system is 2520 kJ.

Problem 5

A tank containing air is stirred by a paddle wheel. The work input to the paddle wheel is 2000 kJ and the heat transferred to the surrounding from the tank is 6000 kJ. Determine the change in the internal energy of the system.

Solution: Given $W = -2000$ kJ, $Q = -6000$ kJ.
From the first law of thermodynamics, for the closed system undergoing a process,

$$Q = \Delta U + W$$
$$-6000 = \Delta U + (-2000)$$
$$\Delta U = -4000 \text{ kJ}$$

The negative sign indicates that there is a drop in internal energy. Thus the internal energy of the system drops by 4000 kJ.

Problem 6

The compressed air in a closed cylinder has an internal energy of 520 kJ/kg and 350 kJ/kg, before and after a certain process, respectively. If the work done by the air in the cylinder is 80 kJ/kg, calculate the heat transfer during the process.

Solution: Given $U_1 = 520$ kJ/kg, $U_2 = 350$ kJ/kg, $W = -80$ kJ/kg.
From the first law of thermodynamics, for the closed system undergoing a process,

$$Q = \Delta U + W$$

As internal energy is a point function, therefore

$$Q = (U_2 - U_1) + W$$
$$Q = (350 - 520) + (-80)$$
$$Q = -250 \text{ kJ}$$

The negative sign indicates that heat is lost from the system to the air. Thus, the heat lost by the system is 250 kJ.

Problem 7

Consider a steam turbine power plant system where the work interactions across the system boundary are: power available at the turbine shaft is 800 kW and the feed pump requires 5 kW of work pump to feed condensate back into the boiler. Heat interaction across the system boundary are: the boiler requires 2700 kJ/kg of heat for steam generation and the condenser rejects 1800 kJ/kg of heat to the cooling water. Calculate the steam flow rate in kg/hr during the cycle.

Solution: Given $W_1 = 800$ kW, $W_2 = -5$ kW, $Q_1 = 2700$ kJ/kg, $Q_2 = -1800$ kJ/kg.
We know that steam turbine power plant operates in a cyclic process. From the first law of thermodynamics, for the closed system undergoing a cycle,

$$\oint dQ = \oint dW$$
$$Q_1 + Q_2 = W_1 + W_2$$
$$\dot{m} \times 2700 - \dot{m} \times 1800 = 800 - 5$$

or steam flow rate

$$\dot{m} = 0.8833 \text{ kg/s}$$

or

$$m = 0.8833 \times 3600 = 3180 \text{ kg/h}$$

Problem 8

A closed system undergoes a thermodynamic cycle consisting of four separate and distinct processes. During a cycle, the net heat transfer is −220 kJ. The system completes 150 cycles per minute. Complete the following table showing the method for each item and determine the net rate of work output in kW.

Process	Heat (kJ/min)	Work (kJ/min)	Internal Energy(kJ/min)
a–b	17580	–8160	25740
b–c	0	4170	-4170
c–d	–3660	17970	–21630
d–a	-14140	-14200	60KJ

Solution: Given $Q_{abcd} = -220$ kJ, N = 150 cycles/min, $Q_{ab} = 17580$ kJ/min, $Q_{bc} = 0$, $Q_{cd} = -3660$ kJ/min, $W_{ab} = -8160$ kJ/min, $W_{bc} = -4170$ kJ/min, $\Delta U_{cd} = -21630$ kJ/min.

For process a–b

$$Q_{ab} = \Delta U_{ab} + W_{ab}$$
$$17580 = \Delta U_{ab} - 8160$$
$$\Delta U_{ab} = 25740 \text{ kJ/min}$$

For process b–c

$$Q_{bc} = \Delta U_{bc} + W_{bc}$$
$$0 = \Delta U_{bc} + 4170$$
$$\Delta U_{bc} = -4170 \text{ kJ/min}$$

For process c–d

$$Q_{cd} = \Delta U_{cd} + W_{cd}$$
$$-3660 = -21630 + W_{cd}$$
$$W_{cd} = 17970 \text{ kJ/min}$$

As N = 150 cycles/min, therefore $Q_{abcd} = -220$ kJ = -220×150 kJ/min = -33000 kJ/min. Also,

$$Q_{abcd} = Q_{ab} + Q_{bc} + Q_{cd} + Q_{da}$$
$$-33000 = 17580 + 0 - 3660 + Q_{da}$$
$$Q_{da} = -46920 \text{ kJ/min}$$

Also during the cycle

$$\oint dQ = \oint dW$$

or

$$Q_{abcd} = W_{ab} + W_{bc} + W_{cd} + W_{da}$$
$$-33000 = -8160 + 4170 + 17970 + W_{da}$$
$$W_{da} = -46980 \text{ kJ/min}$$

For the cyclic process

$$\Delta U_{abcd} = 0$$

therefore

$$\Delta U_{abcd} = \Delta U_{ab} + \Delta U_{bc} + \Delta U_{cd} + \Delta U_{da}$$
$$0 = 25740 - 4170 - 21630 + \Delta U_{da}$$
$$\Delta U_{da} = 60 \text{ kJ/min}$$

Process	Heat (kJ/min)	Work (kJ/min)	Internal Energy(kJ/min)
a–b	17560	–8150	25740
b–c	0	4170	–4170
c–d	–3640	17970	–21630
d–a	–46920	–46980	60

As during the cycle net heat supplied is equal to net work output. Therefore,

Net work output = −220 kJ/min

$$= \frac{-220 \times 150}{60} \text{ kJ/sec} = -550 \text{ kJ/s or } -550 \text{ kW}$$

Problem 9

A piston and cylinder contains a fluid system which passes through a complete cycle of four processes. The heat and work transferred in each process are tabulated below:

Process	Heat (kJ/min)	Work (kJ/min)	
a–b	–6500	–1050	-5450
b–c	0	–3450	3450
c–d	–10200	20400	30600
d–a	32600	0	32600

Show that the data are consistent with the first law of thermodynamics and proceed to evaluate the net work output in kW and change in the internal energy for each process.

Solution: Given $Q_{ab} = -6500$ kJ/min, $Q_{bc} = 0$, $Q_{cd} = -10200$ kJ/min, $Q_{da} = 32600$ kJ/min, $W_{ab} = -1050$ kJ, $W_{bc} = -3450$ kJ, $W_{cd} = 20400$ kJ, $W_{da} = 0$.

Net heat transfer in the cycle

$$\oint dQ = Q_{ab} + Q_{bc} + Q_{cd} + Q_{da}$$
$$= -6500 + 0 - 10200 + 32600$$
$$= 15900 \text{ kJ/min}$$

Net work done during the cycle

$$\oint dW = W_{ab} + W_{bc} + W_{cd} + W_{da}$$
$$= -1050 - 3450 + 20400$$
$$= 15900 \text{ kJ/min}$$

From the above solution it is found that

$$\oint dQ = \oint dW$$

hence the given data is consistent with the first law of thermodynamics.

Net work done during the cycle

$$\oint dW = 13900 \text{ kJ/min} = \frac{15900}{60} \text{ kJ/s} = 265 \text{ kW}$$

For process a–b

$$Q_{ab} = \Delta U_{ab} + W_{ab}$$
$$-6500 = \Delta U_{ab} - 1050$$
$$\Delta U_{ab} = -5450 \text{ kJ/min}$$

For process b–c

$$Q_{bc} = \Delta U_{bc} + W_{bc}$$
$$0 = \Delta U_{bc} = -3450$$
$$\Delta U_{bc} = 3450 \text{ kJ/min}$$

For process c–d

$$Q_{cd} = \Delta U_{cd} + W_{cd}$$
$$-10200 = \Delta U_{cd} + 20400$$
$$\Delta U_{ab} = -30600 \text{ kJ/min}$$

For process d–a

$$Q_{da} = \Delta U_{da} + W_{da}$$
$$32600 = \Delta U_{da} + 0$$
$$\Delta U_{bc} = 32600 \text{ kJ/min}$$

Limitations of First Law of Thermodynamics

The first law of thermodynamics establishes equivalence between the quantity of heat and the mechanical work but does not specify the following:

1. The conditions under which it is possible to convert heat into work.
2. The direction in which transfer of heat takes place.

Processes occur spontaneously in certain directions, but the reverse is not automatically attainable even though the reversal of the processes does not violate the first law. The first law of thermodynamics is necessary but not a sufficient condition for the process to take place. This gap has been bridged by the second law of thermodynamics.

9.3 Second Law of Thermodynamics

The second law of thermodynamics acknowledges that processes proceed in a certain direction but not in the opposite direction. Work is said to be a high-grade energy and heat is said to be a low-grade energy. In a cycle the complete conversion of low-grade energy into high-grade energy is impossible. Heat always flows from a body at a higher temperature to a body at a lower temperature.

The Kelvin–Planck Statement

No heat engine can convert all the heat it receives to useful work. This limitation of heat engines forms the basis for the Kelvin–Planck statement of the second law of thermodynamics, which is expressed as follows:

It is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with bodies at a single fixed temperature.

Cycle

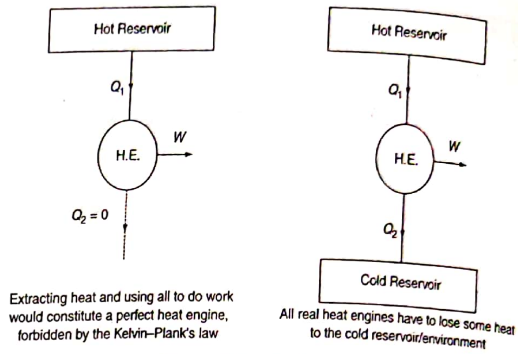


Figure 5 Kelvin–Planck statement.

It states that it is impossible to construct a heat engine that operates in a cycle, receives a given amount of heat from a high-temperature body and does an equal amount of work. The only alternate is that some heat must be transferred from the working fluid at a lower temperature to a low-temperature body. This implies that it is impossible to build a heat engine that has a thermal efficiency of 100%.

Clausius Statement

Clausius statement is related to refrigerators and heat pumps. The Clausius statement is expressed as follows:

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 a higher-temperature body.

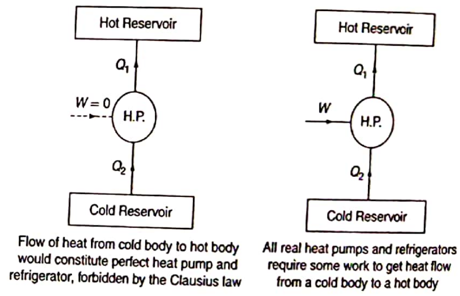


Figure 6 Clausius statement.

It is common knowledge that heat does not flow spontaneously from a cold medium to a warmer one. The Clausius statement does not imply that a cyclic device that transfers heat from a cold medium to a warmer one is impossible to construct. In fact, this is precisely what a common household refrigerator does. It simply states that a refrigerator will not operate unless its compressor is driven by an external power source, such as an electric motor. This way, the net effect on the surroundings involves the consumption of some energy in the form of work, in addition to the transfer of heat from a colder body to a warmer one. That is, it leaves a trace in the surroundings. Therefore, a household refrigerator is in complete compliance with the Clausius statement of the second law.

Like first law of thermodynamics, the second law of thermodynamics is also based on experimental observations. To date, no experiment has been conducted that violates the second law; this can be taken as sufficient evidence of its validity.

Equivalence of Kelvin–Planck and Clausius Statements

Kelvin–Planck's and Clausius statements may appear to be unconnected, but it can easily be shown that they are equivalent in all respects. The equivalence of the two statements will be proved if it is shown that the violation of one statement implies the violation of the second and vice versa.

Violation of Clausius Statement Leads to Violation of Kelvin–Planck Statement

Consider Figure 7(a). Suppose we can construct a heat pump which transfers heat (Q_2) from a low-temperature reservoir to a high-temperature one without using external work, violating Clausius statement. Then, we can couple it with a heat engine in such a way that the heat removed (Q_2) by the heat pump from the low-temperature reservoir is the same as the heat rejected by the heat engine. Now the combined system is a heat engine which converts heat ($Q_1 - Q_2$) to work (W) without any external effect. Thus, it violates the Kelvin–Planck statement.

Violation of Kelvin–Planck Statement Leads to Violation of Clausius Statement

Consider Figure 7(b). Suppose we have a heat engine which can convert heat ($Q_1 - Q_2$) into work ($Q_1 - Q_2$) without rejecting heat anywhere else, violating Kelvin–Plancks statement. Then, we can combine it with a heat pump so that the work produced ($Q_1 - Q_2$) by the engine is used by the pump. Now the combined system is a heat pump which uses no external work and transfers Q_2

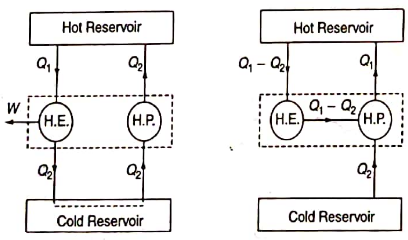


Figure 7 (a) Violation of Clausius statement; (b) violation of Kelvin–Planck's statement.

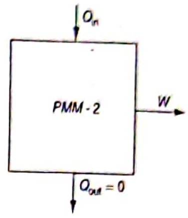


Figure 8 PMM-2.

amount of heat from a body at low temperature to the body at high temperature. This violates the Clausius statement.

Thus, we see that the Clausius and Kelvin–Planck statements are equivalent, and one necessarily implies the other.

9.4 Perpetual Motion Machine of Second Kind (PMM-2)

A perpetual motion machine of the second kind (PMM-2) as shown in Figure 8 is an imaginary engine that, while working in a cycle, converts all the heat input into work. A PMM-2 has a thermal efficiency of 100%. As per the second law of thermodynamics (Kelvin–Planck statement), *the existence of perpetual motion machine of the second kind is impossible.*

The impossibility of having a 100% efficient heat engine is not due to friction or other dissipative effects. It is a limitation that applies to both the idealized and the actual heat engines.

Points to Remember

1. The first law of thermodynamics states that *"During any cycle a system undergoes, the cyclic integral of the heat is proportional to the cyclic integral of the work".*
2. For the closed system undergoing a cycle $\oint dQ = \oint dW$
3. For the closed system undergoing a process $Q = \Delta E + W$
4. Work done for closed system $W = \int_1^2 P\,dV$ where dV is the change in volume at constant pressure P.
5. $\Delta E = m c_v dT$, where specific heat $c_v = 0.718$ kJ/kg for air, m is the mass of air, dT is the change in temperature.
6. The Kelvin–Planck statement for second law of thermodynamics *"It is impossible for a heat engine to produce net work in a complete cycle if it exchanges heat only with bodies at a single fixed temperature."*
7. Clausius statement for second law of thermodynamics *"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 a higher-temperature body."*

Key Terms

Joule Apparatus
First law of thermodynamics
Second law of thermodynamics
Kelvin–Planck statement
Clausius statement
Heat
Work
Energy
Perpetual motion machine of first and second kind

Objective-Type Questions

Multiple-Choice Questions

1. The algebraic sum of work and heat interaction during a cycle is
   a. always negative
   b. always positive
   c. zero
   d. all of these
2. The first law of thermodynamics is based on the
   a. Joule's experiment
   b. Clausius experiment
   c. Newton's experiment
   d. Avogadro's experiment
3. The first law of thermodynamics states
   a. $\oint dQ = \oint dE$
   b. $\oint dQ = \oint dW$
   c. $\oint dE = \oint dW$
   d. $\oint dQ = \oint dU$
4. First law of thermodynamics deals with conservation of
   a. heat
   b. mass
   c. momentum
   d. energy
5. A system undergoing a change of state during which Q amount of heat is added and W amount of work is done, then the net energy that will be stored within the system is $\Delta U =$
   a. $Q - W$
   b. $Q + W$
   c. $Q \times W$
   d. Q/W
6. An isolated system has
   a. constant heat
   b. constant energy
   c. constant work
   d. all of these
7. A perpetual motion machine of first kind is an imaginary device which delivers work continuously
   a. with work as input
   b. with heat as input
   c. either heat or work as input
   d. without any input
8. The maximum efficiency of a heat engine is always
   a. less than 100%
   b. more than 100%
   c. equal to 100%
   d. unpredictable
9. Kelvin Planck's statement is related with
   a. heat engines
   b. refrigerators
   c. heat pumps
   d. all of these
10. The possible kind of perpetual motion machine is the
    a. first
    b. second
    c. both first and second
    d. none of these

Review Questions

1. State first law of thermodynamics for a closed system undergoing a cycle.
2. State first law of thermodynamics for a closed system undergoing a change of state.
3. State and explain the first law of thermodynamics. *[RGPV Feb 2008]*
4. State the first law of thermodynamics and give important consequences stated in the form of corollaries.
5. Explain the perpetual motion machine of first kind.
6. State the limitations of first law of thermodynamics.
7. State the Kelvin–Planck statement of second law of thermodynamics and explain with suitable diagram.
8. State the Clausius statement of second law of thermodynamics. Explain with suitable diagram.
9. State importance of the second law of thermodynamics.
10. State and explain second law of thermodynamics. *[RGPV Jun 2008]*
11. Prove that a device that violates the Kelvin–Planck statement of second law also violates the Clausius statement.
12. Prove that a device that violates the Clausius statement of second law also violates the Kelvin–Planck statement.
13. Establish the equivalence of Kelvin–Planck and Clausius statements.
14. Prove that a system which satisfies Kelvin–Planck statement of second law cannot violate the Clausius statement or vice versa.
15. Explain the perpetual motion machine of first kind.

Problems

1. A system undergoes a cycle composed of four processes. The heat transfers in process a–b, b–c, c–d and d–a are 680 kJ, 120 kJ, –60 kJ and 270 kJ, respectively. The work transfers in the processes a–b, b–c and c–d are 585 kJ, –140 kJ and 280 kJ, respectively. Determine the work interaction during the process d–a.
2. A cylinder containing air comprises expansion and compression strokes in the cycle. During the expansion stroke heat absorbed from the surroundings is 150 kJ and work done by the air on the piston is 71500 Nm. During compression stroke work done on the piston is 8900 Nm. Determine the quantity of heat transferred to or from the system.
3. During one cycle the working fluid in an engine engages in two work interactions – 54 kJ to the fluid and 22 kJ from the fluid – and three heat interactions – two of which are 65 kJ to the fluid and 80 kJ from the fluid. Calculate the magnitude and direction of the third heat interaction.
4. A non-flow process loses 320 kJ of heat and 560 kJ of internal energy. How much work is done and is the process a compression or an expansion?
5. A tank containing air is stirred by a paddle wheel. The work input to the paddle wheel is 2860 kJ and the heat transferred to the surrounding from the tank is 3450 kJ. Determine the change in the internal energy of the system.
6. The compressed air in a closed cylinder has an internal energy of 160 kJ/kg and 450 kJ/kg, before and after a certain process, respectively. If the work done by the air in the cylinder is 210 kJ/kg, calculate the heat transfer during the process.

Review Questions

1. State first law of thermodynamics for a closed system undergoing a cycle.
2. State first law of thermodynamics for a closed system undergoing a change of state.
3. State and explain the first law of thermodynamics. [RGPV Feb 2008]
4. State the first law of thermodynamics and give important consequences stated in the form of corollaries.
5. Explain the perpetual motion machine of first kind.
6. State the limitations of first law of thermodynamics.
7. State the Kelvin–Planck statement of second law of thermodynamics and explain with suitable diagram.
8. State the Clausius statement of second law of thermodynamics. Explain with suitable diagram.
9. State importance of the second law of thermodynamics.
10. State and explain second law of thermodynamics. [RGPV Jun 2008]
11. Prove that a device that violates the Kelvin–Planck statement of second law also violates the Clausius statement.
12. Prove that a device that violates the Clausius statement of second law also violates the Kelvin–Planck statement.
13. Establish the equivalence of Kelvin–Planck and Clausius statements.
14. Prove that a system which satisfies Kelvin–Planck statement of second law cannot violate the Clausius statement or vice versa.
15. Explain the perpetual motion machine of first kind.

Problems

1. A system undergoes a cycle composed of four processes. The heat transfers in process a–b, b–c, c–d and d–a are 680 kJ, 120 kJ, –60 kJ and 270 kJ, respectively. The work transfers in the processes a–b, b–c and c–d are 585 kJ, –140 kJ and 280 kJ, respectively. Determine the work interaction during the process d–a.
2. A cylinder containing air comprises expansion and compression strokes in the cycle. During the expansion stroke heat absorbed from the surroundings is 150 kJ and work done by the air on the piston is 71500 Nm. During compression stroke work done on the piston is 8900 Nm. Determine the quantity of heat transferred to or from the system.
3. During one cycle the working fluid in an engine engages in two work interactions – 54 kJ to the fluid and 22 kJ from the fluid – and three heat interactions – two of which are 65 kJ to the fluid and 80 kJ from the fluid. Calculate the magnitude and direction of the third heat interaction.
4. A non-flow process loses 320 kJ of heat and 560 kJ of internal energy. How much work is done and is the process a compression or an expansion?
5. A tank containing air is stirred by a paddle wheel. The work input to the paddle wheel is 2860 kJ and the heat transferred to the surrounding from the tank is 3450 kJ. Determine the change in the internal energy of the system.
6. The compressed air in a closed cylinder has an internal energy of 160 kJ/kg and 450 kJ/kg, before and after a certain process, respectively. If the work done by the air in the cylinder is 210 kJ/kg, calculate the heat transfer during the process.

7. Consider a steam turbine power plant system where the work interactions across the system boundary are: power available at the turbine shaft is 270 kW and the feed pump requires 9 kW of work pump to feed condensate back into the boiler. Heat interaction across the system boundary is: the boiler requires 842 kJ/kg of heat for steam generation and the condenser rejects 320 kJ/kg of heat to the cooling water. Calculate the steam flow rate in kg/h during the cycle.
8. A closed system undergoes a thermodynamic cycle consisting of four separate and distinct processes. During a cycle, the net heat transfer is 66 kJ. The system completes 200 cycles/min. Complete the following table showing the method for each item, and determine the net rate of work output in kW.

Process	Heat (kJ/min)	Work (kJ/min)	Internal Energy (kJ/min)
a–b	2340	–7330	9670
b–c	–3210	0	–3210
c–d	9060	11220	–2160
d–a	5010	–	–

Answers

Multiple-Choice Questions

1. (c)
2. (a)
3. (b)
4. (d)
5. (a)
6. (d)
7. (d)
8. (a)
9. (a)
10. (d)

Problems

1. 285 kJ
2. 87.4 kJ
3. 82 kJ
4. 240 kJ > –880
5. –590 kJ
6. 80 kJ/kg
7. 0.5 kg/s
8. ΔE_{ab} = 9670 kJ/min; ΔE_{bc} = –3210 kJ/min; ΔQ_{cd} = 9060 kJ/min; ΔQ_{da} = 5010 kJ/min; ΔW_{da} = 9310 kJ/min; ΔE_{da} = - 4300 kJ/min; W_{net} = 220 kW.

12 Refrigeration Systems

LEARNING OBJECTIVES

After completing this chapter, you will learn

- Vapor-compression refrigeration system.
- Vapor-absorption refrigeration system.
- Ozone-depleting refrigerants and their properties.
- Eco-friendly refrigerants and their properties.

Refrigeration is the process of extracting heat from an enclosed space or from a substance in order to cool and rejecting the extracted heat to the atmosphere. Thus, the primary purpose of the refrigeration system is to lower the temperature of the enclosed space and to maintain that lower temperature. In order to satisfy the second law of thermodynamics some form of work must be performed to accomplish this. The performance of refrigerators is expressed in terms of the coefficient of performance (COP) which is defined as the ratio of the cooling effect produced to the work input. Mathematically,

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

The cooling capacity of a refrigerator system is defined as the rate of heat removal from the refrigerated space. It is generally expressed in terms of *tons of refrigeration (TR)*. One ton of refrigeration is defined as the heat that has to be extracted to freeze 1 ton (1000 kg) of water from and at 0°C in 24 h, which is taken equivalent to 210 kJ/min or 3.5 kJ/s.

Out of several refrigeration systems available, two basic types of refrigeration systems are explained below.

12.1 Vapor-Compression Refrigeration System

Vapor-compression refrigeration is used in domestic and commercial refrigerators, large-scale warehouses for storage of foods and meats, refrigerated trucks and railroad cars as well as air-conditioning systems. Industries utilizing large vapor-compression refrigeration system include oil refineries, petrochemical and chemical processing plants and natural gas processing plants.

Working

The vapor-compression refrigeration system uses a circulating liquid refrigerant as the medium which absorbs heat from the space/chamber to be cooled and rejects that heat to the atmosphere. Figure 1 shows the schematic of a single-stage vapor-compression system. It has four basic components, namely, a compressor, a condenser, an expansion valve (or throttle valve) and an evaporator.

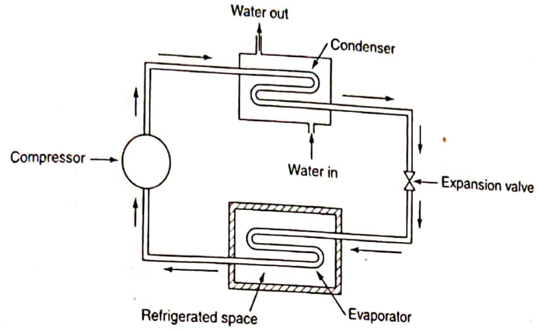


Figure 1 Simple vapor-compression cycle.

Circulating refrigerant enters the compressor in a saturated vapor state. Here it is compressed to a high pressure resulting into a higher temperature of the refrigerant and is in the superheated vapor state.

The hot vapor is then routed through the tubes of a condenser. Here refrigerant rejects its heat to the cool water or cool air flowing outside the tubes. This condenses the refrigerant and the refrigerant comes in the saturated liquid state.

sudden

The saturated liquid is then routed through an expansion valve where it undergoes an abrupt reduction in pressure. The pressure reduction lowers the temperature, colder than the temperature of the enclosed space to be refrigerated.

The cold mixture is then routed through the coil or tubes of the evaporator, lying in the enclosed space. The evaporator coils absorb the heat and cool the air subsequently the substance kept in the enclosed space. The refrigerant leaving the evaporator is in the saturated vapor state which is routed back to the compressor.

12.2 Vapor-Absorption Refrigeration System

The absorption refrigerator is a refrigerator that utilizes a heat source to provide the energy needed to drive the refrigeration system rather than being dependent on electricity to run a compressor. These refrigerators are popular where electricity is unreliable, costly or unavailable, where noise from the compressor is problematic or where surplus heat is available, for example, from turbine exhausts or industrial processes. The most common use is in commercial climate control and cooling of machinery. Absorptive refrigeration is also used to air-condition buildings using the waste heat from a gas turbine or water heater.

Types

The vapor-absorption refrigeration system common in large commercial plants uses (i) ammonia, hydrogen gas and water; (ii) solution of lithium bromide salt and water; (iii) air, water and a salt solution. However, large industrial units generally use ammonia as a refrigerant and water as an absorbent.

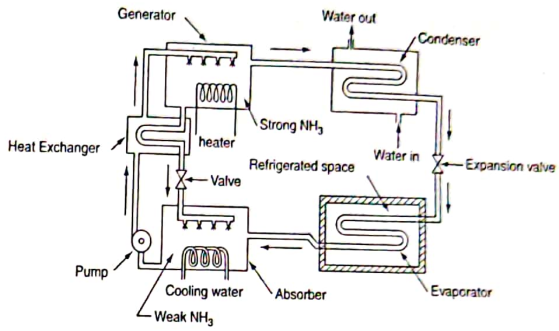


Figure 2 Simple vapor-absorption cycle.

Process

The vapor-absorption refrigeration system differs fundamentally from vapor-compression system only in the method of compressing the refrigerant. An absorber, generator and pump in the absorption refrigerating system replace the compressor of a vapor-compression system. The other components are condenser, expansion valve and evaporator. Figure 2 shows the schematic diagram of a vapor-absorption refrigeration system.

Ammonia vapor is produced in the generator at high pressure from the strong solution of ammonia by an external heating source. The water vapor carried with ammonia is removed in the rectifier and only the dehydrated ammonia gas enters the condenser. High-pressure ammonia vapor is condensed in the condenser. The cooled ammonia solution is passed through a throttle valve and the pressure and temperature of the refrigerant are reduced below the temperature to be maintained in the evaporator. The low temperature refrigerant enters the evaporator. It absorbs the required heat from the evaporator and leaves the evaporator as saturated vapor.

Slightly superheated, low-pressure ammonia vapor is absorbed by the weak solution of ammonia which is sprayed in the absorber. Weak ammonia solution (aqua-ammonia) entering the absorber becomes a strong solution after absorbing ammonia vapor which is pumped to the generator through the heat exchanger. The pump increases the pressure of the strong ammonia solution to the generator pressure.

It may be noted that the strong solution of ammonia coming from the absorber in the heat exchanger is at a lower temperature than the weak ammonia solution coming from the generator. This strong ammonia solution absorbs heat in the heat exchanger from the weak ammonia solution.. The ammonia solution entering the generator becomes weak as NH_3 vapor comes out of it. The weak, high-temperature NH_3 solution from the generator is passed to the heat exchanger into the absorber through the throttle valve. Thus, the pressure of the ammonia liquid is reduced to the absorber pressure by the throttle valve.

12.3 Comparison between Vapor-Compression and Vapor-Absorption Refrigeration Systems

A comparison between the vapor-compression refrigeration system and the vapor-absorption refrigeration system is given in Table 1.

Table 1 Comparison between vapor-compression and vapor-absorption refrigeration systems

S. no.	*Vapor-compression refrigeration system*	*Vapor-absorption refrigeration system*
1.	Uses mechanical work, that is a high-grade energy.	Uses heat, that is a low-grade energy, therefore may be worked on exhaust systems from internal combustion engines, gas turbines, etc.
2.	Moving parts are in the compressor. Hence subjected to more wear, tear and noise.	Moving parts are only in the pump, which is a small element of the system. Hence operation is smooth.
3.	The coefficient of performance (COP) decreases considerably with decrease in evaporator pressure.	The COP of is not affected even though the system works on lower evaporator pressure.
4.	Performance is adversely affected at partial loads.	Performance is not affected at partial loads or reducing loads.
5.	Liquid traces of the refrigerant in the suction line may damage the compressor.	Liquid traces of the refrigerant present in piping at the exit of evaporator constitute no danger.
6.	Automatic operation for controlling the capacity is difficult.	Automatic operation for controlling the capacity is easy.

12.4 Refrigerant Properties

The thermodynamic efficiency of a refrigeration system depends mainly on its operating temperatures. However, important practical issues such as the system design, size, initial and operating costs, safety, reliability, serviceability, etc. depend very much on the type of refrigerant selected for a given application. Owing to several environmental issues such as ozone layer depletion and global warming and their relation to the various refrigerants used, the selection of suitable refrigerant has become one of the most important issues in recent times. Replacement of an existing refrigerant by a completely new refrigerant, for whatever reason, is an expensive proposition as it may call for several changes in the design and manufacturing of refrigeration systems. Hence it is very important to understand the issues related to the selection and use of refrigerants. In principle, any fluid can be used as a refrigerant. Air used in an air cycle refrigeration system can also be considered as a refrigerant. However, the attention is mainly focused on those fluids that can be used as refrigerants in vapor-compression refrigeration systems only.

Selection of refrigerant for a particular application is based on the following requirements:

1. thermodynamic and thermo-physical properties;
2. environmental and safety properties;
3. economics.

Ozone-Depleting Refrigerants and Their Properties

The properties of a few commonly used ozone-depleting refrigerants are given below:

1. R-11

   Formula : CCl_3F (Trichloromonofluoromethane)
   Molecular weight : 137.7 g/mol
   Boiling temperature (at 1.013 bar) : 23.8 C
   Latent heat of vaporization (1.013 bar) : 182.5 kJ/kg

   Critical temperature : 198 C
   Ozone depletion potential : 1
   Global warming potential : 4000
   Ratio of specific heats (C_p/C_v) : 1.12

   It is non-flammable, non-corrosive, non-toxic and stable. The cylinder color code is orange. It is used in large air conditioning systems, industrial heat pumps, etc. Now the manufacture and use of R11 is banned.

2. R-12

   Formula : CCl_2F_2 (Dichlorodifluoromethane)
   Molecular weight : 120.9 g/mol
   Boiling temperature (at 1.013 bar) : –29.8 C
   Latent heat of vaporization (1.013 bar) : 166.9 kJ/kg
   Critical temperature : 112 C
   Ozone depletion potential : 1
   Global warming potential : 7300
   Ratio of specific heats (C_p/C_v) : 1.14

   It is little odor, colorless gas or liquid, non-flammable, non-corrosive, non-toxic and stable. The cylinder color code is white. It is used in domestic refrigerators, small air conditioners, water coolers, small cold storages, etc. Owing to its ozone-depleting potential, it is currently replaced by R134a (1,1,1,2-tetrafluoroethane), R142b (Chloro-1-difluoro-1,1-ethane) or R409a (mixture containing 60 % of R12).

3. R-22

   Formula : $CClF_2$ (Chlorodifluoromethane)
   Molecular weight : 86.5 g/mol
   Boiling temperature (at 1.013 bar) : –40.8°C
   Latent heat of vaporization (1.013 bar) : 233.9 kJ/kg
   Critical temperature : 96 C
   Ozone depletion potential : 0.05
   Global warming potential : 1500
   Ratio of specific heats (C_p/C_v) : 1.166

   It is non-flammable, non-corrosive, non-toxic and stable. The cylinder color code is green. It was earlier used in air conditioning systems, cold storages, etc. It will be replaced by R-134A.

Eco-Friendly Refrigerants and their Properties

The properties of a few commonly used eco-friendly refrigerants are given below:

1. R-134A

   Formula : $H_2FC\text{-}CF_3$ (1,1,1,2-Tetrafluoroethane)
   Molecular Weight : 102 g/mol
   Boiling temperature (at 1.013 bar) : –26.6 C
   Latent heat of vaporisation (1.013 bar) : 215.9 kJ/kg
   Critical temperature : 100.9 C
   Global warming potential : 1200
   Ratio of specific heats (C_p/C_v) : 1.14

   It is immiscible in mineral oils, highly hygroscopic. It is used in domestic refrigerators, water coolers, automobile, air conditioning systems, etc. It has replaced R12 and R22. No replacement of R-134A is required as it has no ozone depletion potential.

2. NH_3

Formula	: NH_3 (Ammonia)
Molecular weight	: 17 g/mol
Boiling temperature (at 1.013 bar)	: –33.5 C
Latent heat of vaporization (1.013 bar)	: 1371.2 kJ/kg
Critical temperature	: 132.4 C
Ratio of specific heats (C_p/C_v)	: 1.3

It is highly flammable and poisonous if inhaled in large quantity. So for any design or application, careful consideration must be given. It is toxic, incompatible with copper, highly efficient, inexpensive and available. It is used in cold storage, warehouse plants, ice-cream manufacturing, food freezing plants, etc. No replacement of NH_3 is required as it has no ozone depletion potential and global warming potential.

3. R-290

Formula	: C_3H_8 (Propane)
Molecular weight	: 44.1 g/mol
Boiling temperature (at 1.013 bar)	: –42.1 C
Latent heat of vaporization (1.013 bar)	: 425.3 kJ/kg
Critical temperature	: 96.6 C
Global warming potential	: 3
Ratio of specific heats (C_p/C_v)	: 1.13

It is highly flammable.

4. R-407C

Formula	: CH_2F_2, CF_3CHF_2, CH_2FCF_3
Composition	: R407C is a ternary blend of hydrofluorocarbon. 23% of R32, 25% of R125 and 52% of R134a
Molecular weight	: 86.2 g/mol
Boiling temperature (at 1.013 bar)	: –43.4 C
Latent heat of vaporization (1.013 bar)	: 249.9 kJ/kg
Critical temperature	: 86.2 C
Global warming potential	: 1610
Ratio of specific heats (C_p/C_v)	: 1.19

It is colorless, volatile liquid with ethereal and faint sweetish odor. It should not be mixed with air above atmospheric pressure for leak testing or any other purpose.

5. R-410A

Formula	: CH_2F_2, CHF_2CF_3
Composition	: R-410A is a binary blend of hydrofluorocarbon 50% of R32 and 50% of R125
Molecular weight	: 72.6 g/mol
Boiling temperature (at 1.013 bar)	: –51.6 C
Latent heat of vaporization (1.013 bar)	: 256.7 kJ/kg
Critical temperature	: 70.2 C
Global warming potential	: 1890
Ratio of specific heats (C_p/C_v)	: 1.24

It is colorless.

6. R-417A

Formula	: CH_2FCF_3, CHF_2CF_3, C_4H_{10}
Composition	: R-417A is a ternary blend of hydrofluorocarbon 50% of R134a, 46.6% of R125 and 3.4% of R600
Molecular weight	: 106.7 g/mol
Boiling temperature (at 1.013 bar)	: –38.0 C
Critical temperature	: 89.9 C
Global warming potential	: 0
Ratio of specific heats (C_p/C_v)	: 1.15

It is a suitable candidate for the replacement of R22 for both refrigeration and air conditioning applications.

Points to Remember

1. Coefficient of performance (COP) is defined as the ratio of the cooling effect produced to the work input.
2. One ton of refrigeration is defined as the heat that has to be extracted to freeze 1 ton (1000 kg) of water from and at 0 C in 24 h, which is taken equivalent to 210 kJ/min or 3.5 kJ/s.
3. The basic components of vapor-compression refrigeration system are compressor, condenser, expansion valve (or throttle valve) and evaporator.
4. The basic components of vapor-absorption refrigeration system are absorber, generator, pump, condenser, expansion valve and evaporator.
5. R-11, R-12 and R-22 are the ozone-depleting refrigerants.
6. R-134A, NH_3, R-29 0, R-407C, R-410A, R-417A are the eco-friendly refrigerants.

Key Terms

Coefficient of performance	Ozone-depleting refrigerants	NH3
Cooling capacity	R-11	R-290
Vapor-compression refrigeration system	R-12	R-407C
Vapor-absorption refrigeration system	R-22	R-410A
	Eco-friendly refrigerants	R-417A
	R-134A	

Objective-Type Questions

Multiple Choice Questions

1. Coefficient of performance of a refrigerators is defined as

a. $\frac{\text{Work input}}{\text{Cooling effect}}$

b. $\frac{\text{Work input}}{\text{Heating effect}}$

c. $\frac{\text{Cooling effect}}{\text{Work input}}$

d. $\frac{\text{Heating effect}}{\text{Work input}}$

14 Air Standard Cycles

LEARNING OBJECTIVES

After completing this chapter, you will learn

- Need of air standard cycles
- Carnot cycle and its efficiency.
- Otto cycle and its efficiency.
- Diesel cycle and its efficiency.
- Comparison of Otto and diesel cycles.

The cycle followed by a *heat engine which uses air as the working medium* is known as an air standard cycle. As the analysis of an air standard cycle is idealistic and simple, it is also called ideal cycle. The engines running on such cycle are called ideal engines.

14.1 Assumptions

In order to make the analysis simple, the following assumptions are made:

1. The engine operates in a closed cycle. (The working fluid at the end of the cycle remains unchanged and is at the same thermodynamic state as at the beginning of the cycle.)
2. The working fluid is a perfect gas with constant specific heats and molecular weight corresponding to values at room temperature.
3. The processes are reversible. (There is no mechanical or frictional loss.)
4. The heat addition and heat rejection processes are merely heat transfer processes. (It takes place by bringing engine in contact with thermal reservoirs, a constant temperature source.)
5. There is no heat transfer from the apparatus to the atmosphere.
6. No chemical reactions occur during the cycle.

14.2 Need of Analysis

The assumptions result in an analysis of air standard cycle that is far from the actual heat engine cycle, but is valuable for the following reasons:

1. It gives the maximum ideal efficiency of a specific thermodynamic cycle.
2. It shows the effect of principal variables of the cycle on the performance of actual engine.
3. It helps to evaluate the effect of relative size of the engine.

14.3 Terminology

Following terms are frequently used in internal combustion engines in addition to those explained in Chapter 13 – Section 13.2.

1. **Compression Ratio:** It is the *ratio of the volume of the fluid occupied before compression to the volume of the fluid occupied after compression*. Mathematically, it is defined as the ratio of total cylinder volume to the clearance volume:

$$\text{Compression ratio, } r = \frac{v_s + v_c}{v_c}$$

The higher the compression ratio, better will be the performance of an engine.

2. **Thermal Efficiency:** The thermal efficiency (η_{th}) of a thermodynamic cycle is defined as the *fraction of heat supplied to a thermodynamic cycle is converted to work*. Mathematically, it is expressed as

$$\eta_{th} = \frac{\text{Net workdone}}{\text{Heat supplied}} = \frac{\sum W}{Q_S} = \frac{Q_S + Q_R}{Q_S} \quad 1 - \frac{Q_R}{Q_S}$$

where Q_S is the heat supplied and Q_R is the heat rejected in the cycle.

3. **Mean Effective Pressure:** It is defined as *the average pressure acting on the piston* which will produce the same output as is done by the varying pressure during a cycle. It can be derived from the indicator diagram as

$$P_m = \frac{\text{Area of indicator diagram}}{\text{Length of indicator diagram}}$$

As the area of the indicator diagram defines the work done and the length of the indicator diagram defines swept volume, mean effective pressure may also be written as

$$P_m = \frac{\text{Work done in a cycle}}{\text{Swept volume}}$$

It is usually expressed in bar or N/m².

14.4 Carnot Cycle and its Efficiency

This cycle was proposed by Sadi Carnot in 1824 and has the highest possible efficiency for any cycle. It is operated with *two isothermal and two isentropic processes*. Figures 1 and 2 show the P–V and T–s diagrams of the cycle, respectively.

$T_2 = T_1^{\gamma-1}$

$Q_{23} = RT\ln\left(\frac{V_3}{V_2}\right)$

$Q_{41} = RV\ln\left(\frac{V}{V}\right)$

$\eta = Q_S - Q_R$

$1 - \frac{T_R}{T_{RC}}$

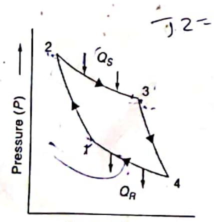


Figure 1 P–V curve for Carnot cycle.

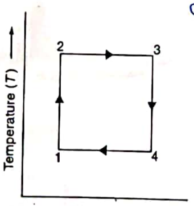


Figure 2 T–s curve for Carnot cycle.

At the start of the cycle, consider the engine to contain air at a thermodynamic state indicated by point 1. The sequence of operations is as follows.

1. Air is compressed isentropically from point 1 to point 2. The temperature of the air rises from T_{min} to T_{max}.
2. Heat is added isothermally causing the air to expand from point 2 to point 3.
3. The air now expands isentropically from point 3 to point 4, reducing the temperature from T_{max} to T_{min}.
4. Air rejects the heat isothermally and is compressed to reoccupy the initial state, that is, point 1.

Thus, the heat addition and rejection processes are isothermal while the compression and expansion processes are isentropic. Let, T_{max} be the absolute temperature at salient points 2 and 3, T_{min} be the absolute temperature at salient points 1 and 4. Let v_1, v_2, v_3 and v_4 be the specific volumes at salient points/states 1, 2, 3 and 4 respectively.

Heat transfer per unit mass from point 1 to point 2 and from point 3 to point 4 is

$$Q_{1-2} = Q_{3-4} = 0$$

Heat supplied per unit mass from point 2 to point 3 is

$$Q_{2-3} = Q_S = P_2 v_2 \ln\frac{v_3}{v_2}$$

As $P_2 v_2 = RT_{max}$ and compression ratio during isothermal process $r = v_3/v_2$, therefore

$$Q_{2-3} = RT_{max}\ln(r)$$

Heat rejected per unit mass from point 4 to point 1 is

$$Q_{4-1} = Q_R = P_4 v_4 \ln\frac{v_4}{v_1}$$

As $P_4 v_4 = RT_{min}$ and $v_4/v_1 = r$, therefore

$$Q_{4-1} = RT_{min}\ln(r)$$

The thermal efficiency of the cycle is given by

$$\eta_{th} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{Q_S - Q_R}{Q_S}$$

q_r

$$\eta_{th} = 1 - \frac{RT_{min}\ln(r)}{RT_{max}\ln(r)}$$

$\eta = 1 - (T_{min})$

$q_s . T_{max}$

$$\eta_{th} = 1 - \frac{T_{min}}{T_{max}} \tag{1}$$

Thus, the thermal efficiency of the Carnot cycle is only a function of the maximum and minimum temperatures of the cycle. For optimum Carnot efficiency, the engine should take all the heat at as high a temperature as possible and should reject the heat at as low a temperature as possible. As efficiency of the cycle depends only on the maximum and minimum temperature limits, it is independent of the properties of the working fluid.

It is impossible to construct an engine that will work on the Carnot cycle, because, in such an engine it would be necessary for the piston to move very slowly during the isothermal processes and very quickly during the isentropic processes. This variation in the speed of the piston cannot be achieved in practice. Also, a very long piston stroke would produce only a small amount of work most of which would be absorbed by the friction of the moving parts of the engine.

Problem 1

An engine working on Carnot cycle produces 150 kJ of work. If the temperature limits for the engine is 477 °C and 27 °C, calculate thermal efficiency of the cycle and heat added during the process.

Solution: Given $T_{max} = 477 + 273 = 750$ K, $T_{min} = 27 + 273 = 300$ K.
Thermal efficiency of the Carnot cycle is

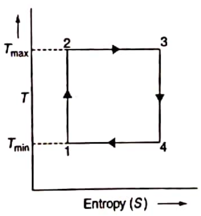
$$\eta_{th} = 1 - \frac{T_{min}}{T_{max}} = 1 - \frac{300}{750} = 0.6 \text{ or } 60\%$$

Heat added during the process is

$$Q_S = \frac{\text{Work done}}{\eta_{th}} = \frac{150}{0.6} = 250 \text{ kJ}$$

Problem 2

The heat rejected by an engine working on Carnot cycle is 1.5 times the work done. If the difference in the temperature limits of the cycle is 300 °C calculate (i) the thermal efficiency, (ii) maximum and the minimum temperatures of the cycle.



Solution: Given $Q_R = 1.5 \times$ Work done, $T_{max} - T_{min} = 300$ °C.
We know that work done $= Q_S - Q_R$

(i) It is given that

$$Q_R = 1.5 \times (Q_S - Q_R)$$

$$Q_R = \frac{1.5}{2.5} Q_S = 0.6\, Q_S$$

Thermal efficiency is

$$\eta_{th} = \frac{Q_S - Q_R}{Q_S} = 1 - \frac{Q_R}{Q_S} = 1 - \frac{0.6 \times Q_S}{Q_S} = 0.4 \text{ or } 40\%$$

(ii) Thermal efficiency is also given by

$$\eta_{th} = \frac{T_{max} - T_{min}}{T_{max}}$$

$$0.4 = \frac{300}{T_{max}}$$

It may be noted that 300 C representing the temperature difference. Therefore it also represents the difference of absolute temperatures. So we need not to add 273 to it.
Maximum temperature of the cycle

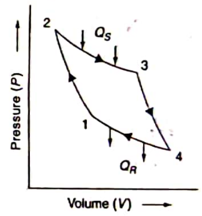
$$T_{max} = \frac{300}{0.4} = 750 \text{ K} = 477 \text{ °C}$$

Because $T_{max} - T_{min} = 300$ °C, therefore minimum temperature of the cycle

$$T_{min} = 477 \text{ °C} - 300 \text{ °C} = 177 \text{ °C}$$

Problem 3

A Carnot engine works between the temperature limits of 750 K and 300 K and the pressure limits of 50 bar and 1 bar. Calculate (i) pressure at intermediate salient points, (ii) heat supplied and rejected per kg of air, (iii) work done per kg of air and (iv) thermal efficiency of the cycle.



Solution: Given $T_1 = T_4 = T_{min} = 300$ K, $T_2 = T_3 = T_{max} = 750$ K, $P_2 = 50 \times 10^5$ N/m², $P_4 = 1 \times 10^5$ N/m². Considering air as the working fluid, $R = 0.287$ kJ/kg K, $c_p = 1.005$ kJ/kg K, $c_v = 0.718$ kJ/kg K and $\gamma = 1.4$.

(i) For isentropic process 1 – 2,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}$$

$$\frac{P_1}{P_2} = \left(\frac{T_1}{T_2}\right)^{\gamma/(\gamma-1)}$$

$$P_1 = P_2 \left(\frac{T_1}{T_2}\right)^{\gamma/(\gamma-1)}$$

$$P_1 = 50\left(\frac{300}{750}\right)^{1.4/(1.4-1)}$$
$$= 2.02 \text{ bar}$$

For isentropic process 3 – 4,

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3}\right)^{(\gamma-1)/\gamma}$$

$$\frac{P_3}{P_4} = \left(\frac{T_3}{T_4}\right)^{\gamma/(\gamma-1)}$$

$$P_3 = P_4\left(\frac{T_3}{T_4}\right)^{\gamma/(\gamma-1)}$$

$$P_3 = 1\left(\frac{750}{300}\right)^{1.4/(1.4-1}$$
$$= 24.7 \text{ bar}$$

(ii) Heat supplied during process 2 – 3,

$$Q_{2-3} = Q_S = P_2 v_2 \ln\frac{v_3}{v_2} = RT_{max} \ln\frac{P_2}{P_3}$$

$$Q_S = 0.287 \times 750 \times \ln\frac{50}{24.7} = 151.8 \text{ kJ/kg}$$

Heat rejected during process 4 – 1,

$$Q_{4-1} = Q_R = P_4 v_4 \ln\frac{v_4}{v_1} = RT_{min} \ln\frac{P_1}{P_4}$$

$$Q_R = 0.287 \times 300 \times \ln\frac{2.02}{1} = 60.7 \text{ kJ/kg}$$

(iii) Work done, $W = Q_S - Q_R = 151.8 - 60.7 = 91.1$ kJ/kg

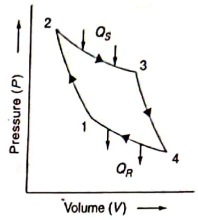
(iv) Thermal efficiency of the Carnot cycle,

$$\eta_{th} = 1 - \frac{T_{min}}{T_{max}} = 1 - \frac{300}{750} = 0.6 \text{ or } 60\%$$

Problem 4

A Carnot cycle having air as the working fluid has its maximum pressure and temperature in a cycle limited to 20 bar and 377 K. The ratio of isentropic compression is 5 and isothermal expansion is 2. Calculate (i) the minimum temperature in the cycle, (ii) heat supplied and rejected in the process and (iii) thermal efficiency of the cycle.

Solution: Given $T_2 = T_3 = T_{max} = 377 + 273 = 650$ K, $P_2 = 20 \times 10^5$ N/m², $v_1/v_2 = 5$, $v_3/v_2 = 2$. Considering air as the working fluid, $R = 0.287$ kJ/kg K, $c_p = 1.005$ kJ/kg K, $c_v = 0.718$ kJ/kg K and $\gamma = 1.4$.



(i) For isentropic process 1 – 2,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\gamma-1}$$

Therefore, minimum temperature

$$T_{min} = T_1 = T_2\left(\frac{v_2}{v_1}\right)^{\gamma-1} = 650\left(\frac{1}{5}\right)^{1.4-1} = 341.4 \text{ K} = 68.4°\text{C}$$

(ii) Heat supplied during process 2 – 3 is

$$Q_{2-3} = Q_S = P_2 v_2 \ln\frac{v_3}{v_2} = RT_{max} \ln\frac{v_3}{v_2}$$

$$Q_S = 0.287 \times 650 \ln 2 = 129.3 \text{ kJ/kg}$$

For isentropic process 3 – 4,

$$\frac{T_4}{T_3} = \left(\frac{v_4}{v_3}\right)^{\gamma-1}$$

$$\frac{v_3}{v_4} = \left(\frac{T_3}{T_4}\right)^{1/(\gamma-1)}$$

Heat rejected during process 4 – 1 is

$$Q_{4-1} = Q_R = P_4 v_4 \ln\frac{v_1}{v_4} = RT_{min} \ln\frac{v_1}{v_4}$$

$$Q_R = RT_{min} \ln\left(\frac{v_1}{v_2} \times \frac{v_2}{v_3} \times \frac{v_3}{v_4}\right) = 0.287 \times 341.4 \ln\left[5 \times \frac{1}{2} \times \left(\frac{T_3}{T_4}\right)^{1/(\gamma-1)}\right]$$

$$Q_R = 0.287 \times 341.4 \ln\left[5 \times \frac{1}{2} \times \left(\frac{650}{341.4}\right)^{1/(1.4-1)}\right] = 247.5 \text{ kJ/kg}$$

(iii) Thermal efficiency of the Carnot cycle is

$$\eta_{th} = 1 - \frac{T_{min}}{T_{max}} = 1 - \frac{341.4}{650} = 0.475 \text{ or } 47.5\%$$

14.5 Otto Cycle and its Efficiency

The Otto cycle, which was first proposed by a Frenchman, Beau de Rochas, in 1862, was first used on an engine built by a German, Nicholas A. Otto, in 1876. This is the equivalent air cycle for reciprocating spark ignition engines. It operates on *two isentropic and two isochoric* (constant volume) *processes*. Figures 3 and 4 show the P–V and T–s diagrams of the cycle.

At the start of the cycle, consider that the piston is at its outer position of the cylinder. It contains air at a thermodynamic state indicated by point 1. The sequence of operations is as follows.

1. Air is compressed isentropically from point 1 to point 2.
2. Heat is added at constant volume, raising the pressure from point 2 to point 3.
3. The air at high pressure expands isentropically from point 3 to point 4.
4. Heat is rejected at constant volume, reoccupying the initial state, point 1.

The cycle is also called a constant volume or explosion cycle because heat is supplied to the working fluid at constant volume. Let T_1, T_2, T_3 and T_4 be the absolute temperatures at salient points 1, 2, 3 and 4, respectively. Also let v_1, v_2, v_3 and v_4 be the specific volumes at salient points/states 1, 2, 3 and 4, respectively. Let c_p be the specific heat at constant pressure, c_v the specific heat at constant volume, γ the ratio of specific heat at constant pressure to constant volume and r the compression ratio. Heat transfer per unit mass from point 1 to point 2 and from point 3 to point 4 is

$$Q_{1-2} = Q_{3-4} = 0$$

The heat supplied per unit mass of air from point 2 to point 3 is

$$Q_{2-3} = Q_S = c_v(T_3 - T_2)$$

The heat rejected per unit mass of air from point 4 to point 1 is

$$Q_{4-1} = Q_R = c_v(T_4 - T_1)$$

The thermal efficiency of the Otto cycle is given by

$$\eta_{th} = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{Q_S - Q_R}{Q_S}$$

$$\eta_{th} = 1 - \frac{T_4 - T_1}{T_3 - T_2} \quad (2)$$

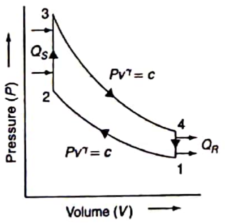


Figure 3 *P–V* curve for Otto cycle.

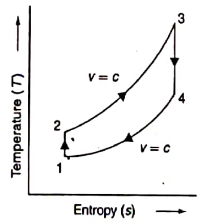


Figure 4 *T–s* curve for Otto cycle.

For adiabatic process 1–2 we have

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1}\right)^{\gamma-1} = \left(\frac{1}{r}\right)^{\gamma-1}$$

$$T_1 = T_2\left(\frac{1}{r}\right)^{\gamma-1} \quad (3)$$

And for adiabatic process 3 – 4 we have

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4}\right)^{\gamma-1} = \left(\frac{v_2}{v_1}\right)^{\gamma-1} = \left(\frac{1}{r}\right)^{\gamma-1}$$

$$T_4 = T_3\left(\frac{1}{r}\right)^{\gamma-1} \quad (4)$$

Hence, substituting Eqs. (3) and (4) in Eq. (2), we get

$$\eta_{th} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

$$= 1 - \frac{T_3\left(\frac{1}{r}\right)^{\gamma-1} - T_2\left(\frac{1}{r}\right)^{\gamma-1}}{T_3 - T_2}$$

$$= 1 - \frac{(T_3 - T_2)\left(\frac{1}{r}\right)^{\gamma-1}}{T_3 - T_2}$$

$$= 1 - \frac{1}{r^{\gamma-1}} \quad (5)$$

Equation (5) shows that the thermal efficiency of the theoretical Otto cycle increases with increase in compression ratio (i.e., ratio of specific heats) but is independent of the heat added (independent of load) and initial conditions of pressure, volume and temperature.

Figure 5 shows a plot of thermal efficiency versus compression ratio for an Otto cycle for three different values of γ. It is seen that the increase in efficiency is significant at lower compression ratios.

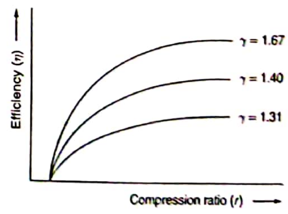


Figure 5 Effect of compression ratio and adiabatic index on efficiency.

Mean Effective Pressure

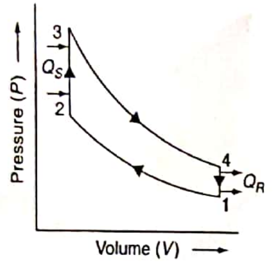
The mean effective pressure of the Otto cycle can be derived as

$$\text{mep} = \frac{P_1 r}{(r-1)(\gamma-1)}[(r^{\gamma-1}-1)(\alpha-1)]$$

where P_1 is pressure before compression, that is, at point 1; α is the explosion ratio ($\alpha = P_3/P_2$); r is the compression ratio and γ is the adiabatic index.

Problem 5

In an Otto cycle the pressures at the beginning and the end of the isentropic compression are 1 bar and 20 bar, respectively. Find the compression ratio and the air standard efficiency of the cycle.



Solution: Given $P_1 = 1$ bar, $P_2 = 20$ bar. Considering air as the working fluid we have $\gamma = 1.4$.
For the isentropic process 1 – 2 the compression ratio is

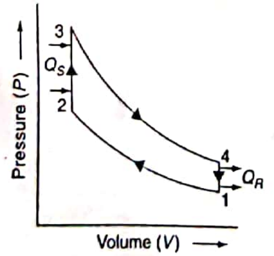
$$r = \frac{v_1}{v_2} = \left(\frac{P_2}{P_1}\right)^{1/\gamma} = \left(\frac{20}{1}\right)^{1/1.4} = 8.5$$

For Otto cycle air standard efficiency

$$\eta_{th} = 1 - \frac{1}{r^{\gamma-1}} = 1 - \frac{1}{8.5^{1.4-1}} = 0.575 \text{ or } 57.5\%$$

Problem 6

In an engine working on ideal Otto cycle, the air at a temperature of 27 °C is compressed isentropically until the temperature reaches 450 °C. Find the compression ratio and the air standard efficiency.



Solution: Given $T_1 = 27 + 273 = 300$ K, $T_2 = 450 + 273 = 723$ K.
For the isentropic process 1 – 2 the compression ratio is

$$r = \frac{v_1}{v_2} = \left(\frac{T_2}{T_1}\right)^{1/(\gamma-1)} = \left(\frac{723}{300}\right)^{1/(1.4-1)} = 9$$

For Otto cycle air standard efficiency is

$$\eta_{th} = 1 - \frac{1}{r^{\gamma-1}} = 1 - \frac{1}{9^{1.4-1}} = 0.585 \text{ or } 58.5\%$$

Problem 7

An engine is working on ideal Otto cycle having a cylinder bore of 200 mm and stroke of 450 mm. If the clearance volume is 2×10^6 mm^3, find the compression ratio and the air standard efficiency of the engine.

Solution: Given $D = 200$ mm $= 0.2$ m, $L = 450$ mm $= 0.45$ m, $v_c = 2 \times 10^{-3}$ m^3, $\gamma = 1.4$.

$$\text{Swept volume, } v_s = \frac{\pi}{4}D^2L = \frac{\pi}{4}(0.2)^2 \times 0.45 = 0.014137 \text{ m}^3$$

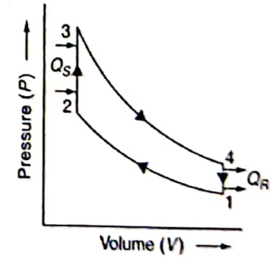
$$\text{Compression ratio, } r = \frac{v_s + v_c}{v_c} = \frac{0.014137 + 0.002}{0.002} = 8.068$$

For Otto cycle air standard efficiency is

$$\eta_{th} = 1 - \frac{1}{r^{\gamma-1}} = 1 - \frac{1}{8.068^{1.4-1}} = 0.566 \text{ or } 56.6\%$$

Problem 8

An engine working on ideal Otto cycle is supplied with air at 0.1 MPa and 35 °C. The compression ratio is 9 and heat supplied is 1800 kJ/kg. Calculate (i) maximum pressure and temperature of the cycle, (ii) the cycle efficiency, (iii) the work done per unit mass of air and (iv) mean effective pressure.



Solution: Given $P_1 = 0.1$ MPa, $T_1 = 35 + 273 = 308$ K, $r = 9$, $Q_s = 1800$ kJ/kg.

(i) For the isentropic process 1 – 2,

$$\frac{T_2}{T_1}=\left(\frac{v_1}{v_2}\right)^{\gamma-1}=\left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}$$

Therefore, temperature at point 2 is

$$T_2=T_1\left(\frac{v_1}{v_2}\right)^{\gamma-1}=308\,(9)^{1.4-1}=741.7\text{ K}$$

and pressure at point 2 is

$$P_2=P_1\left(\frac{v_1}{v_2}\right)^{\gamma}=0.1(9)^{1.4}=2.167\text{ MPa}$$

Heat supplied per unit mass,

$$Q_S=c_v\left(T_3-T_2\right)$$

$$1800=0.718\left(T_3-741.7\right)$$

Therefore, the maximum temperature of the cycle, $T_3 = 3248.66$ K or 2975.66 °C.

Maximum pressure of the cycle,

$$P_3=\frac{T_3}{T_2}\times P_2=\frac{3248.66}{741.7}\times 2.167=9.5\text{ MPa}$$

(ii) Otto cycle thermal efficiency,

$$\eta_{th}=1-\frac{1}{r^{\gamma-1}}=1-\frac{1}{9^{1.4-1}}=0.585\text{ or }58.5\%$$

(iii) Work done during the cycle $= Q_S \times \eta_{th} = 1800 \times 0.585 = 1053$ kJ/kg

(iv) From characteristic gas equation

$$v_1=\frac{RT_1}{P_1}=\frac{0.287\times10^3\times308}{0.1\times10^6}=0.884\text{ m}^3/\text{kg}$$

$$v_2=\frac{v_1}{r}=\frac{0.884}{9}=0.0982\text{ m}^3/\text{kg}$$

$$\text{Swept volume}=v_1-v_2=0.884-0.0982=0.7858\text{ m}^3/\text{kg}$$

Mean effective pressure is

$$P_m=\frac{\text{Work done in a cycle}}{\text{Swept volume}}$$

$$=\frac{1053\times10^3}{0.7858}=1.34\times10^6\text{ N/m}^2=1.34\text{ MPa}$$

It can also be determined as

$$\text{Explosion ratio, }\alpha=\frac{P_3}{P_2}=\frac{9.5}{2.167}=4.38$$

In this case the mean effective pressure is given by

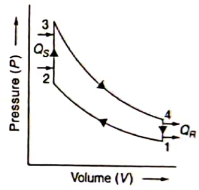
$$P_m=\frac{P_1 r}{(r-1)(\gamma-1)}\left[\left(r^{\gamma-1}-1\right)(\alpha-1)\right]$$

$$=\frac{1\times10^5\times14}{(9-1)(1.4-1)}\left[\left(9^{\gamma-1}-1\right)(4.38-1)\right]$$

$$=1.34\text{ MPa}$$

Problem 9

An engine working on ideal Otto cycle has pressure and temperature at the beginning of compression as 0.1 MPa and 40 °C, respectively. The air standard efficiency is 55% and heat is rejected at 540 kJ/kg. Calculate (i) compression ratio of the engine, (ii) work done per unit mass of air, (iii) pressure and temperature at the end of compression and (iv) maximum pressure in the cycle.



Solution: Given $P_1 = 0.1$ MPa, $T_1 = 40 + 273 = 313$ K, $\eta_{th} = 0.55\%$, $Q_R = 540$ kJ/kg.

(i) Otto cycle thermal efficiency,

$$\eta_{th}=1-\frac{1}{r^{\gamma-1}}$$

$$0.55=1-\frac{1}{r^{1.4-1}}$$

$$r=7.36$$

Therefore, the compression ratio $r = 7.36$.

(ii) Efficiency is also given by

$$\eta_{th}=\frac{Q_S-Q_R}{Q_S}$$

$$0.55=\frac{Q_S-540}{Q_S}$$

$$Q_S=1200\text{ kJ/kg}$$

Therefore, heat supplied per unit mass $Q_S = 1200$ kJ/kg.

Work done per kg of air $= Q_S - Q_R = 1200 - 540 = 660$ kJ/kg.

(iii) For the isentropic process 1 – 2,

$$\frac{T_2}{T_1}=\left(\frac{v_1}{v_2}\right)^{\gamma-1}=\left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}$$

Therefore, temperature at the end of compression is

$$T_2=T_1\left(\frac{v_1}{v_2}\right)^{\gamma-1}=313(7.36)^{1.4-1}=695.5\text{ K}$$

and pressure at point 2 is

$$P_2=P_1\left(\frac{v_1}{v_2}\right)^{\gamma}=0.1(7.36)^{1.4}=1.635\text{ MPa}$$

(iv) As heat supplied per unit mass

$$Q_S=c_v(T_3-T_2)$$

$$1200=0.718(T_3-695.5)$$

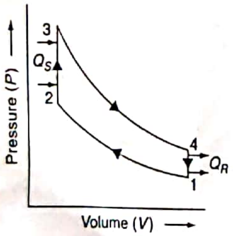
therefore, the maximum temperature of the cycle, $T_3 = 2366.8$ K or 2093.8 °C.

Maximum pressure of the cycle is

$$P_3=\frac{T_3}{T_2}\times P_2=\frac{2366.8}{695.5}\times 1.635=5.56\text{ MPa}$$

Problem 10

An Otto engine works between the temperature limits of 300 K and 2500 K and the pressure limits of 1 bar and 50 bar. Find (a) the air standard efficiency and (b) the net work done per unit mass of air.



Solution: Given $T_1 = 300$ K, $T_3 = 2500$ K, $P_1 = 1 \times 10^5$ N/m², $P_3 = 50 \times 10^5$ N/m².

Compression ratio, $r=\frac{v_1}{v_2}=\frac{P_2}{P_1}\times\frac{T_1}{T_2}$

For constant volume heat addition process, $\frac{P_2}{T_2}=\frac{P_3}{T_3}$

Therefore,

$$r=\frac{v_1}{v_2}=\frac{P_3}{P_1}\times\frac{T_1}{T_3}=\frac{50}{1}\times\frac{300}{2500}=6$$

Air standard efficiency is

$$\eta_{th}=1-\frac{1}{r^{\gamma-1}}=1-\frac{1}{6^{1.4-1}}=0.5116\text{ or }51.16\%$$

$$\frac{T_2}{T_1}=\left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}$$

$$T_2=T_1\left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}=300\left(\frac{50}{1}\right)^{(1.4-1)/1.4}=917.36\text{ K}$$

Heat supplied is given by

$$Q_S=c_v(T_3-T_2)$$

$$=0.718(2500-917.36)=1136.33\text{ kJ/kg}$$

Efficiency is also given by

$$\eta_{th}=\frac{\text{Work done}}{Q_S}$$

$$0.5116=\frac{\text{Work done}}{1136.33}$$

$$\text{Work done}=581.4\text{ kJ/kg}$$

14.6 Diesel Cycle and its Efficiency Joules Cycle

This cycle, proposed by a German engineer, Dr. Rudolph Diesel, to describe the processes of his engine, is also called the constant pressure cycle. This is the equivalent air cycle for reciprocating slow speed compression ignition engine. It operates on two isentropic, one isobaric (constant pressure) and one isochoric (constant volume) processes. Figures 6 and 7 show the P–V and T–s diagrams of the cycle, respectively.

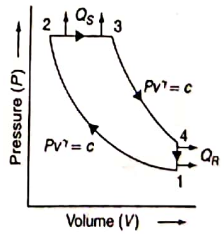


Figure 6 *P–V* curve for diesel cycle.

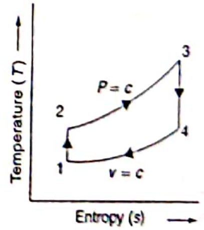


Figure 7 *T–s* curve for diesel cycle.

- **Water Cooled Engine:** Here heat from the cylinder walls is transferred to cooling water, circulated in water jacket.

6. On the basis of arrangement of cylinders as
   - Horizontal Engine
   - Vertical Engine
   - In-Line Engine
   - V-Engine
   - Radial Engine
   - Opposed Cylinder Engine
   - Opposed Piston Engine
7. On the basis of field of application as
   - Stationary Engine
   - Marine Engine
   - Automobile Engine
   - Aero Engine
   - Locomotive Engines
8. On the basis of speed of crankshaft as
   - Low-Speed Engine
   - Medium-Speed Engine
   - High-Speed Engine
9. On the basis of valve arrangement as
   - Overhead Valve Engine
   - T-Head Valve Engine
   - L-Head Valve Engine
   - F-Head Valve Engine
10. On the basis of method of governing as
    - Hit and Miss Governed Engine
    - Quality Governed Engine
    - Quantity Governed Engine

15.2 Components

Figure 1(a) shows the schematic diagram of a four-stroke petrol engine and Figure 1(b) shows the schematic diagram of a two-stroke petrol engine. The main components of the internal combustion and their functions are as follows:

1. **Cylinder:** The cylinder is the main body of the engine in which piston reciprocates. Here the combustion of fuel takes place to develop power.
2. **Piston and Piston Rings:** The function of the piston and piston rings is to confine the gases in the combustion space and thus transmit the full force of expansion to the connecting rod and the crankshaft.
3. **Connecting Rod:** It connects the piston at one end and crank at the other end. The function of the connecting rod is to transmit the reciprocating motion of the piston and convert it into rotary motion of the crankshaft.
4. **Crankshaft:** It is mounted in the bearing and can rotate freely. The power required for any purpose is taken from crankshaft only.

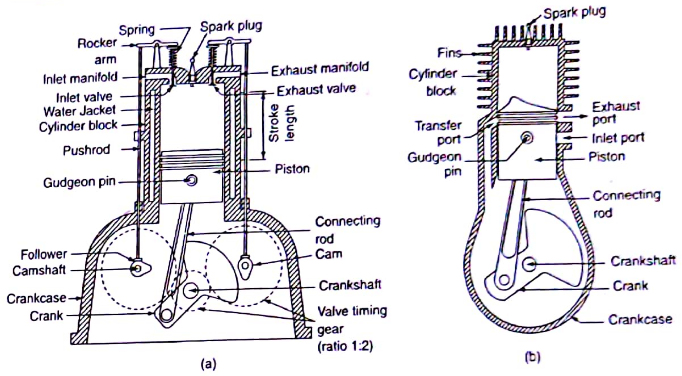


Figure 1 (a) Four-stroke petrol engine; (b) two-stroke petrol engine.

5. **Crankcase:** It is the main body of the engine to which the cylinders are attached and which contains the crankshaft. In four-stroke engines it serves as an oil sump for the storage of lubricating oil.
6. **Flywheel:** It is a wheel mounted on the crankshaft which stores excess energy during the power stroke, returns that energy during the other strokes and maintains a fairly constant output torque on the crankshaft. In other words, it reduces the cyclic variation of speed.
7. **Governor:** The function of the governor is to control the fluctuation of engine speed due to changes in load. This is made possible by regulating the quantity of charge in petrol engines and regulating the amount of fuel in diesel engines.
8. **Camshaft and Valve Mechanism:** These are used in four-stroke engines. Camshafts are driven by the crankshaft at exactly half its rotational speed. They operate the intake and exhaust valves through the cams, followers, push rods and rocker arms.
9. **Ignition System:** It is used in case of petrol engine. Its function is to produce a spark between the electrodes of the spark plug and ignite the charge at the precise instant.
10. **Injection System:** It is used in the case of diesel engine. Its function is to supply the correct amount of fuel at the precise instant. The nozzle breaks the fuel stream called atomize and distributes it in the combustion chamber of the engine.

15.3 Working of Four-Stroke Petrol Engine

In a four-stroke petrol engine, a piston moves up and down, total four times, completing a cycle. In other words, the cycle of operation is completed in four strokes of the piston or two revolution of the crankshaft. These engines are widely used in motor cycles and motor cars. The main components of the engine are cylinder, piston, connecting rod, crankshaft, inlet and exhaust valves, valve operating mechanism and ignition system.

1-4

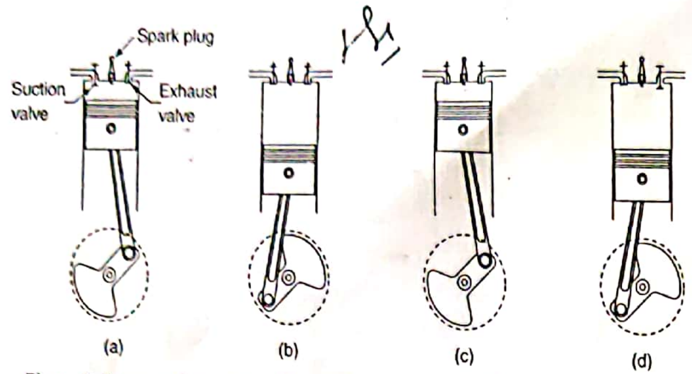


Figure 2 Sequence of operation of four stroke petrol engine: (a) Suction stroke; (b) compression stroke; (c) power stroke; (d) exhaust stroke.

Figures 2(a)–(d) show the following series of operations of an ideal four-stroke petrol engine, considering the piston is initially at the TDC.

1. Suction or Intake Stroke: When the piston is about to move downward, toward the BDC, the inlet valve is open by the valve operating mechanism. The exhaust valve remains closed. As the piston moves downward, the suction is created and the charge consisting of fuel–air mixture is sucked into the cylinder.

Bottom Dead Centre.

2. Compression Stroke: When the piston reaches the BDC the inlet valve is closed. The exhaust valves remains in the closed position. As the piston moves upward, the charge gets compressed. The compression ratio usually ranges from 6 to 12.

diff 3. Power or Expansion Stroke: At the end of compression stroke, the ignition system produces a spark between the spark plug electrodes. The charge is ignited instantaneously which may be approximated as heat addition at constant volume. The pressure in the cylinder is 4–5 times what it was before ignition. Both valves remain in the closed position. The high pressure of the burnt gases forces the piston to move towards BDC. Of the four strokes the power is produced only during this stroke.

4. Exhaust Stroke: At the end of the power stroke the exhaust valve opens and the inlet valve remains closed. A part of the burnt gases escapes and the cylinder pressure falls to atmospheric level. The piston starts moving upward and sweeps the burnt gases out of the cylinder. When the piston reaches TDC, the exhaust valve gets closed.

15.4 Working of Four-Stroke Diesel Engine

In a four-stroke diesel engine, a piston moves up and down, total four times, completing a cycle. In other words, the cycle of operation is completed in four strokes of the piston or two revolution of the crankshaft. These engines are widely used in heavy vehicles such as buses, trucks and earth-moving machineries. The main components of the engine are cylinder, piston, connecting rod, crankshaft, inlet and exhaust valves, valve operating mechanism and fuel injection system.

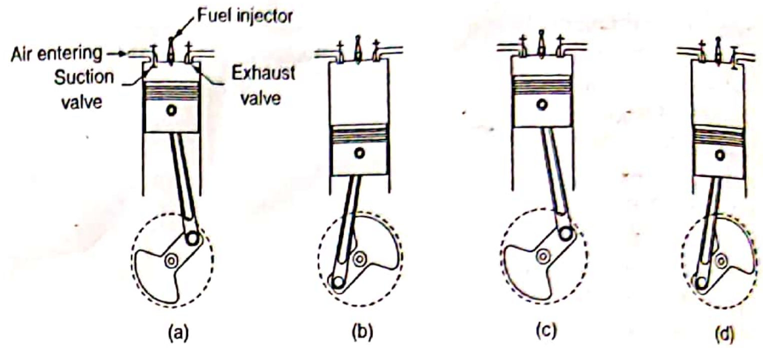


Figure 3 Sequence of operation of four stroke diesel engine: (a) Suction stroke; (b) compression stroke; (c) power stroke; (d) exhaust stroke.

Figures 3(a)–(d) show the following series of operations of an ideal four-stroke diesel engine, considering the piston is initially at the TDC.

1. Suction or Intake Stroke: When the piston is about to move downward, toward the BDC, the inlet valve is open by the valve operating mechanism. The exhaust valve remains closed. As the piston moves downward, the suction is created and the fresh air is sucked into the cylinder.
2. Compression Stroke: When the piston reaches the BDC the inlet valve is closed. The exhaust valves remains in the closed position. As the piston moves upward the air gets compressed. The compression ratio usually ranges from 16 to 22.
3. Power or Expansion Stroke: At the end of compression stroke, the fuel is being injected in the form of fine spray into the engine, called atomization. The temperature of the compressed air is sufficient to auto ignite the fuel without the need of spark. The supply of the fuel is continued during a part of the expansion stroke so that the combustion may occur at a constant pressure. Both valves are in the closed position. The high pressure of the burnt gases forces the piston to move towards the BDC. Of the four strokes the power is produced only during this stroke.

diff

4. Exhaust Stroke: At the end of the expansion stroke the exhaust valve opens and the inlet valve remains closed. A part of the burnt gases escape and the cylinder pressure falls to atmospheric level. The piston starts moving upward and sweeps the burnt gases out of the cylinder. When the piston reaches the TDC, the exhaust valve gets closed.

15.5 Working of Two-Stroke Petrol Engine

In a two-stroke petrol engine, a piston moves up and down, total two times, completing a cycle. In other words, the cycle of operation is completed in two strokes of the piston or one revolution of the crankshaft. These engines are widely used in mopeds and scooters.

The main components of the engine are cylinder, piston, connecting rod, crankshaft and ignition system. Instead of valve and valve mechanism, the two-stroke engine contains three ports, namely exhaust port, transfer port and inlet port. These ports are made by cutting holes in the cylinder wall at different levels. Charge is fed into the cylinder through transfer port using the closed crank-case compression. A specific shape is given to the piston crown, usually known as deflector, to prevent the fresh charge to escape from the exhaust port without combustion.

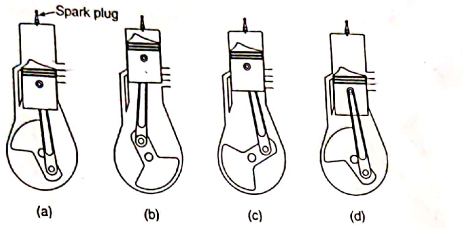


Figure 4 Sequence of operation of two-stroke petrol engine: (a) Suction stroke; (b) compression stroke; (c) power stroke; (d) exhaust stroke.

Figures 4(a)–(d) show the following series of operations of an ideal two-stroke petrol engine, considering the piston is moving downward and transfer port is open. Doubt

1. **Suction or Intake Stroke:** When the piston is moving down towards the BDC, first the exhaust port is opened and then the transfer port is opened to the cylinder. The charge consisting of air–fuel mixture from the crankcase continues entering into the cylinder through the transfer port. Admission of the charge ends after the piston moves past the BDC and goes up in the cylinder to close the inlet port. Further upward movement of the piston closes the exhaust port.
2. **Compression Stroke:** When both the exhaust and the transfer ports are closed and piston is moving up in the cylinder, the compression of the charge takes place. The compression ratio usually ranges from 6 to 12. After the piston has travelled more than three-fourth of its way towards the TDC, the inlet port gets uncovered (open) to the crankcase side. The fresh charge enters into the crankcase.
3. **Power or Expansion Stroke:** At the end of compression stroke, the ignition system produces a spark through the spark plug. The charge is ignited instantaneously, which may be approximated as heat addition at constant volume. The pressure in the cylinder is 4–5 times what it was before ignition. The high pressure of the burnt gases forces the piston to move towards the BDC. Before piston has travelled less than one-fourth of its way towards the BDC, the inlet port gets covered (closed) to the crankcase side. The entry of the charge into the crankcase stops and its compression begins.
4. **Exhaust Stroke:** After the piston has travelled more than halfway down in the cylinder, the exhaust port is uncovered (open). A part of the burnt gases escapes and the cylinder pressure falls to atmospheric level. Soon after that, the inlet port is uncovered (open). Now the exhaust gases are swept out with the help of fresh charge called scavenging. The deflector on the piston crown also helps in sweeping action and at the same time prevents the fresh charge to get carried with the exhaust gas. Both ports remain uncovered until the piston moves up in the cylinder.

15.6 Working of Two-Stroke Diesel Engine

In a two-stroke diesel engine, a piston moves up and down, total two times, completing a cycle. In other words, the cycle of operation is completed in two strokes of the piston or one revolution of the crankshaft. These engines are widely used in motor boats and generators.

The main components of the engine are cylinder, piston, connecting rod, crankshaft and fuel injection system. Instead of valve and valve mechanism, the two-stroke diesel engine contains three ports, namely exhaust port, transfer port and inlet port. These ports are made by cutting holes in the cylinder

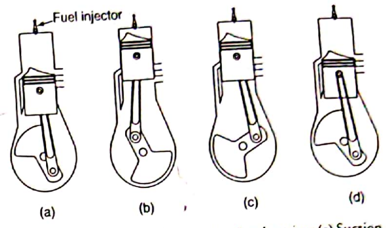


Figure 5 Sequence of operation of two stroke diesel engine: (a) Suction stroke; (b) compression stroke; (c) power stroke; (d) exhaust stroke.

wall at different levels. Air is fed into the cylinder through transfer port using the closed crank-case compression. A specific shape is given to the piston crown, usually known as deflector, to prevent the fresh air to escape from the exhaust port without combustion.

Figures 5(a)–(d) show the following series of operations of an ideal two-stroke diesel engine, considering the piston is moving downward and transfer port is open.

1. **Suction or Intake Stroke:** When the piston is moving down towards the BDC, first the exhaust port is opened and then the transfer port is opened to the cylinder. The fresh air from the crankcase starts entering into the cylinder through the transfer port. Admission of the charge ends after the piston moves past the BDC and goes up in the cylinder to close the inlet port. Further upward movement of the piston closes the exhaust port.
2. **Compression Stroke:** When both the exhaust and the transfer ports are closed and piston is moving up in the cylinder, the compression of the charge takes place. The compression ratio usually ranges from 16 to 22. After the piston has travelled more than three-fourth of its way towards the TDC, the inlet port gets uncovered (open) to the crankcase side. The fresh charge enters into the crankcase.
3. **Power or Expansion Stroke:** At the end of compression stroke, the fuel is being injected in the form of fine spray into the engine, called atomization. The temperature of the compressed air is sufficient to auto ignite the fuel without the need of spark. The supply of the fuel is continued during a part of the expansion stroke so that the combustion may occur at a constant pressure. The high pressure of the burnt gases forces the piston to move towards the BDC. Before piston has traveled less than one-fourth of its way towards the BDC, the inlet port gets covered (closed) to the crankcase side. The entry of the charge into the crankcase stops and its compression begins.
4. **Exhaust Stroke:** After the piston has travelled more than halfway down in the cylinder the exhaust port is uncovered (open). A part of the burnt gases escape and the cylinder pressure falls to atmospheric level. Soon after that, the inlet port is uncovered (open). Now the exhaust gases are swept out with the help of fresh air called scavenging. The deflector on the piston crown also helps in sweeping action and at the same time prevents the fresh air to get carried with the exhaust gas. Both ports remain uncovered until the piston moves up in the cylinder.

15.7 Comparison of Petrol and Diesel Engines

The comparison of petrol and diesel engines [i.e., spark ignition (SI) and compression ignition (CI) engines] is shown in Table 1. It may be noted that for comparison of two engines they should be of same size and run at the same speed.

Table 1 Comparison of petrol and diesel engines

S. no.	Petrol engine (SI engine)	Diesel engine (CI engine)
1.	Works on Otto cycle.	Works on diesel cycle.
2.	Petrol is used as fuel.	Diesel is used as fuel.
3.	Air–fuel mixture is induced in the cylinder during the suction stroke.	Only air is induced in the cylinder during the suction stroke.
4.	The charge is ignited with the help of spark plug.	The fuel is injected in the form of fine spray. The temperature of the compressed air auto-ignites the fuel.
5.	Air–fuel ratio ranges from 10 to 20.	Air–fuel ratio ranges from 18 to 100.
6.	Compression ratio is in the range of 6 to 12.	Compression ratio is in the range of 15 to 22.
7.	It is lighter and cheaper because of low compression ratio.	It is heavier and costlier because of high compression ratio.
8.	Maximum efficiency is lower due to low compression ratio.	Maximum efficiency is higher due to higher compression ratio.
9.	The starting of the engine is easy due to low compression ratio.	The starting of engine is little difficult due to high compression ratio.
10.	It is a high-speed engine.	It is a relatively low-speed engine.
11.	Employed in light duty vehicles such as scooters, motorcycles, cars, etc.	Employed in heavy duty vehicles such as buses, trucks, tractors, etc.

15.8 Comparison of Four-Stroke and Two-Stroke Engines

The comparison of two-stroke and four-stroke engines is shown in Table 2.

Table 2 Comparison of four-stroke and two-stroke engines

S. no.	Four-stroke engine	Two-stroke engine
1.	The cycle is completed in four strokes of the piston or in two revolutions of the crankshaft. Thus one power stroke is obtained in every two revolutions of crankshaft.	The cycle is completed in two strokes of the piston or in one revolutions of the crankshaft. Thus one power stroke is obtained in each revolution of crankshaft.
2.	Develops less power.	Develops more power.
3.	Lesser cooling and lubrication required.	Greater cooling and lubrication required.
4.	Contains valves and valve mechanism.	Contains ports.
5.	Initial cost is higher.	Initial cost is lower.
6.	Volumetric efficiency is higher.	Volumetric efficiency is lower.
7.	Thermal efficiency is higher. Part load efficiency is higher.	Thermal efficiency is lower. Part load efficiency is lower.
8.	Engine is heavy and bulky.	Engine is lighter and compact.
9.	Heavier flywheel is required.	Lighter flywheel is required.
10.	Less polluting because suction and exhaust strokes occur at different time.	More polluting because a part of the charge is lost through exhaust port.
11.	Used in cars, buses, trucks, etc.	Used in mopeds, scooters, etc.

15.9 Comparison of External Combustion and Internal Combustion Engines

The comparison of external combustion and internal combustion engines is shown in Table 3.

Table 3 Comparison of external combustion and internal combustion engines

S. no.	External combustion engine	Internal combustion engine
1.	The combustion of fuel takes place outside the engine.	The combustion of fuel takes place inside the engine.
2.	The working pressure and temperature inside the engine are low.	The working pressure and temperature inside the engine are high.
3.	As the combustion is outside the cylinder, it can use any type of fuel, be it solid, liquid or gaseous.	As the combustion is inside the cylinder, only liquid or gaseous fuel can be used.
4.	It is large in size and cumbersome.	It is small in size and compact.
5.	It has high weight to power ratio.	It has low weight to power ratio.
6	It takes reasonable time to start.	It can be started instantaneously.
7	The efficiency is nearly 15–20%.	The efficiency is nearly 30–35%.
8.	Steam engines, steam turbines, stirling engine fall under this category.	Petrol engine, diesel engine, wankel engine, etc. fall under this category.

Points to Remember

1. Four-stroke engine requires four strokes of the piston or two revolutions of crankshaft to complete a working cycle.
2. Two-stroke engine requires two strokes of the piston or one revolution of crankshaft to complete a working cycle.
3. In spark ignition engine an electric spark ignites the mixture.
4. In compression ignition engine heat developed due to compression of air auto-ignites the injected fuel.
5. Main components of the internal combustion include cylinder, piston, connecting rod, crankshaft, crankcase, flywheel.
6. Compression ratio of petrol engine is in the range of 6–12 whereas compression ratio of diesel engine is in the range of 15–22.
7. Two-stroke engines produces more power than the four-stroke engines when the sizes of the engines are same and they run at same speed. Thus, to obtain higher power from a four-stroke engine cylinders are made of larger capacity.

Key Terms

Four-stroke engine
Two-stroke engine
Petrol engine
Diesel engine
Spark ignition engine
Compression ignition engine
Suction stroke
Compression stroke
Expansion stroke or power stroke
Exhaust stroke
Compression ratio
Atomization
Scavenging