CHAPTER 1

Introduction

1.1 Prime Movers

Prime mover is a device which converts natural source of energy into mechanical work to drive machines for various applications.

In olden days, man had to depend for power on his own physical strength and on animals like horse, bullock etc. As the horse was most important, the unit of power was named 'horse power' for the power developed by prime movers.

Petrol engine, diesel engine, steam turbine, gas turbine are few examples of prime movers.

1.2 Sources of Energy

Conventional sources of energy derived from nature for driving prime movers are coal, petroleum, natural gas, flow of river water, atom etc. Today some non-conventional sources of energy like solar, wind, biogas, biomass, tide, ocean waves, geothermal etc. have also been developed.

Coal, petroleum and natural gas are fuels. Petrol, diesel and kerosene are derived from petroleum. All these fuels are most important sources of energy. Heat energy produced by burning of these fuels may be converted to mechanical work by heat engines.

Another useful source of energy is flow of river water. Dam may be constructed across the river. The potential energy of water collected on upstream side of dam, is used to drive hydraulic turbine that generates the power.

Energy released from atom is nuclear energy. Heat energy produced by fission or fusion of atoms may be converted to mechanical work by steam turbines.

The non-conventional sources of energy mentioned above are on the way of development. These will be needed more in future when the conventional sources would be depleted. Solar energy is available freely. It is renewable and non-polluting source of energy. It may be used to produce steam to run steam turbine. Solar photovoltaic cells may be used to produce electricity.

1.3 Types of Prime Movers

Prime movers may be classified according to the sources of energy utilized by them. The main two types are:

1. Thermal prime movers
2. Hydraulic prime movers

Some other types are:

3. Wind mill
4. Tidal
5. Wave

1. A prime mover which converts heat energy available from different sources into mechanical work is known as thermal prime mover. They are further classified as (a) heat engines (b) nuclear power plants.

   Prime movers using heat energy produced by burning of fuel are called heat engines. Petrol engine, diesel engine, steam engine, steam turbine, gas turbine etc., are examples of heat engines. These engines may be either external combustion engines or internal combustion (I.C) engines.

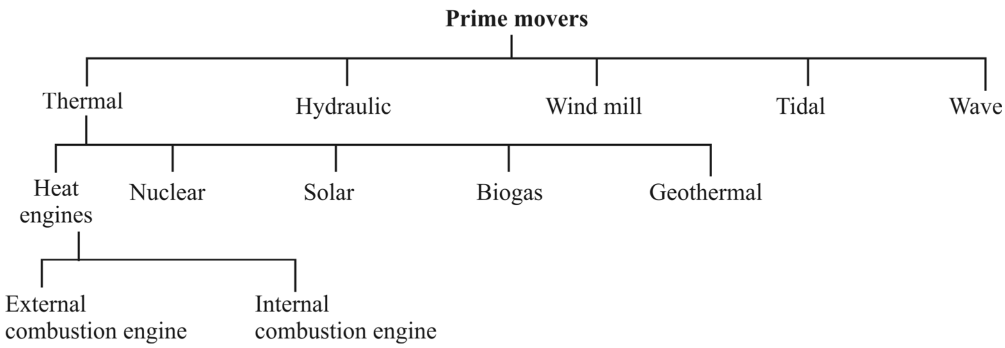
   Nuclear power plant uses nuclear heat energy obtained by fission or fusion of atom.

   Solar power plant, biogas plant and geothermal plant are also thermal prime movers as they use heat energy to generate power.

2. Hydraulic prime movers utilize potential energy of river water and convert it into mechanical work. All hydraulic turbines are hydraulic prime movers.

   Other non-conventional prime movers include wind mill, tidal and wave power plants.

   Thus, types of prime movers may be represented as follows:



1.4 Force and Mass

We will follow SI (system international) system of units.

Mass of the body is defined as the amount of matter contained in it. Its unit is kilogramme (kg). It is denoted by m. Mass of the body always remains constant.

Force is the product of mass and acceleration of the body upon which it is applied.

Thus, force = mass × acceleration

i.e. $F = ma$ …..(1.1)

Unit of mass is kg and unit of acceleration is m/s^2. So, the unit of force is $kg\text{-}m/s^2$. This unit is known as Newton (N). Thus, $1N = 1\ kg\text{-}m/s^2$.

One Newton is that force which when applied to a body of mass 1 kg produces an acceleration of 1 m/s^2 in it. This is a derived unit. The larger units are kN and MN.

The weight (W) of a body is the gravitational force of earth acting on the body. It is the product of mass of the body and local gravitational acceleration g.

i.e. $W = mg$ N …..(1.2)

The value of g at sea level is 9.80665 m/s^2 (approximately 9.81)

The weight of a body of mass 1 kg is considered 1 kgf.

∴ weight 1 kgf = 1 × 9.81 N

∴ 1 kgf = 9.81 N

1.5 Pressure

Pressure is defined as normal force per unit area of the surface.

i.e. $$\text{Pressure} = \frac{\text{force}}{\text{area}}$$

∴ $$P = \frac{F}{A}$$ …..(1.3)

SI unit of pressure will be N/m^2. This unit is also known as Pascal.

i.e. $$Pa = \frac{N}{m^2}$$

One Pascal equals to force of 1 N acting on area of $1m^2$. Pascal is a small unit. The larger units are kPa and MPa.

The other unit of pressure is bar.

$$1\ bar = 10^5\ Pa$$

Pressure of air at mean sea level is 1.01325 bar. This is known as 1 atmosphere, denoted by 1 atm.

i.e. 1 atm = 1.01325 bar

Atmospheric pressure is also equal to the pressure developed by a mercury column of 760 mm. Atmospheric pressure in kgf/cm^2 unit is 1.033 kgf/cm^2.

Some of the pressure measuring instruments are Bourdon pressure gauge, U-tube manometer, barometer etc. Most of the instruments indicate pressure relative to atmospheric pressure, i.e. pressure above the atmospheric pressure. This pressure is called the 'gauge pressure'. The actual pressure is known as absolute pressure.

So, absolute pressure = gauge pressure + atmospheric pressure. …..(1.4)

When system pressure is less than atmospheric, the gauge pressure becomes negative. This negative gauge pressure is called vacuum. Thus, vacuum is the absolute pressure less than atmospheric.

If h = difference in heights of fluid in two limbs of U-tube manometer, m

g = gravitational acceleration, m/s^2

ρ = density of manometric fluid, kg/m^3

then $$p = \rho g h \ \frac{N}{m^2} \quad \text{.....(1.5)}$$

1.6 Work

Work is said to be done when a body, under the action of force, is moving in the direction of force. The magnitude of work is the product of force and the distance moved in the direction of force.

Thus, work = force × distance

i.e. $W = F \times l$ …..(1.6)

This work is the mechanical work mentioned above. The SI unit of work will be Newton-meter (Nm), also known as Joule (J). One Joule is the amount of work done when a force of one Newton acts through a distance of one meter. The larger units are kJ and MJ.

When work is done by a system, it is taken positive, while when it is done on a system, it is taken negative.

When a constant pressure p is exerted on the piston of area A inside the cylinder, work is done due to piston displacement l. This work is

$$W = F \times l = (p \times A) \times l = p \times (A \times l)$$
$$= pV \quad \text{.....(1.7)}$$

where V = volume swept by the piston

When a fluid having initial volume V_1 expands to a final volume V_2, work done

$$W = p\,(V_2 - V_1) \qquad \text{.....(1.8)}$$

Pressure-volume diagram and work:

The graph drawn by taking pressure on y-axis and volume on x-axis is called pressure-volume or P-V diagram. Fig 1.1 shows a P-V diagram.

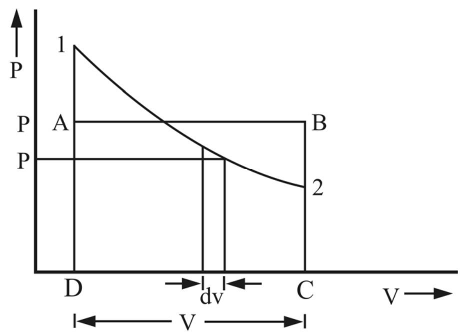


Fig. 1.1 P-V diagram.

If pressure p is constant, area of p-V diagram is area ABCD which is equal to p × V.

Work done is also equal to P × V.

So, area of P-V diagram represents amount of work done.

Now consider the case where pressure varies from 1 to 2 as shown in Fig. 1.1. Assume that the pressure P remains constant for a small change of volume dV. The small amount of work done dW will be represented by area pdV.

So, $$dW = pdV$$

Therefore, the total amount of work done from 1 to 2 will be the sum of all small areas pdv.

i.e. $$W = \int_1^2 PdV \qquad \text{.....(1.9)}$$

This is the total area under curve 1-2.

Thus in all cases, area of P-V diagram represents the amount of work done.

Flow work: The flow work is the energy required to make the fluid flow across the boundary of control volume or open system (Fig. 1.2).

If a fluid of volume V flows into a cylinder against pressure p, it has to do work equal to pV to move the piston. In other words, the fluid possesses the energy equal to pV. This energy is flow work or flow energy.

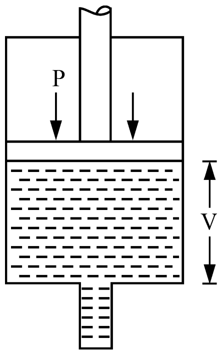


Fig. 1.2 Flow work.

Shaft work: When a shaft is rotated by motor as shown in Fig. 1.3, work is said to be done on shaft.

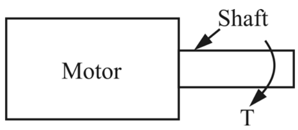


Fig. 1.3 Shaft work.

If T is the torque applied to shaft and dθ is the small angular displacement of the shaft, the shaft work will be

$$W = \int_1^2 T d\theta \qquad .....(1.10)$$

1.7 Power

Power is defined as the rate of doing work or work done per unit time.

i.e. $$\text{Power} = \frac{\text{Work done}}{\text{time}}$$

So, $$P = \frac{W}{t}$$

Unit of power will be Joule/second (J/s). It is called Watt (W). The larger units are kW and MW.

The unit of power in MKS system is horse power (hp). The work done at the rate of 75 kgf-m per sec is equal to 1 hp.

Also, 1 hp = 735.5 W or 0.7355 kW

The power developed by an engine is termed as 'indicated power'. Power developed at the shaft of the engine is termed as 'brake power'.

The power lost due to friction in the engine is termed as 'friction power'. It is the difference between indicated power and brake power.

1.8 Energy

The energy of a body is its capacity for doing work. So, the unit of energy is same as that of work i.e. Joule. The larger units are kJ and MJ.

Another important unit of energy is kilowatt-hour (kWh). Energy consumed in one hour by 1 kW power supply is called 1 kWh.

$$1 \text{ kWh} = 1000 \text{ Wh} = 1000 \frac{J}{s} \times 3600 \text{ s} = 36 \times 10^5 \text{ J}$$

This unit is important in electrical engineering.

There are different forms of energy such as 1. mechanical energy; 2. thermal energy; 3. electrical energy; 4. chemical energy; 5. nuclear energy etc. One form of energy can be readily converted into another form, but the total amount of energy remains constant. This is known as law of conservation of energy.

There are two kinds of mechanical energy :

(a) Potential energy, (b) Kinetic energy

(a) ***Potential energy:*** The energy possessed by a body by virtue of its position is called its potential energy. If a body is raised to a height z metre, its potential energy is

$$PE = mgz \quad J \qquad .....(1.12)$$

(b) ***Kinetic energy:*** The energy possessed by a body by virtue of its motion is called its kinetic energy. If a body is moving at a velocity v m/s, its kinetic energy is

$$KE = \frac{1}{2} mV^2 \quad J \qquad .....(1.13)$$

1.9 Heat

Heat is one form of energy. So, its unit is Joule. It may be converted into work or other forms of energy. Heat can be transferred from one body to the other when temperature difference exists between them. If heat is added to the system, it is taken as positive. If heat is rejected by the system, it is taken as negative.

1.10 Temperature

Temperature is a measure of degree of hotness or coldness of a body. Its unit in SI system is Kelvin (K). The melting point of ice at atmospheric pressure is taken as 273 K, and boiling point of water is taken as 373 K.

For practical purposes, the Celsius scale for measuring temperature is more common. Formerly it was known as centigrade scale. It is denoted by degree Celsius (^{o}C). In this scale, at atmospheric pressure, freezing point of water is taken as 0 ^{o}C and boiling point of water is taken as 100 ^{o}C. One division of celsius scale is equal to one division of kelvin scale. The relation between kelvin and celsius scales is

$$K = {}^{o}C + 273 \qquad \text{.....(1.14)}$$

One more unit of temperature is degree Fahrenheit (^{o}F). Its relation with celsius scale is

$$ {}^{o}F = \frac{9}{5} \times {}^{o}C + 32 \qquad \text{.....(1.15)}$$

Temperature is measured by the instruments known as thermometer and pyrometer.

1.11 Units of Heat

As heat is one form of energy, its unit is Joule. The larger units are kJ and MJ.

In metric system, calorie (cal) and kcal are taken as the units of heat. The quantity of heat required to raise the temperature of 1 kg of water through 1 ^{o}C is known as 1 kcal.

$$1 \text{ kcal} = 4186 \text{ J} = 4.186 \text{ kJ}$$

1.12 Specific Heat Capacity

The specific heat capacity (also called specific heat) of a substance is defined as the amount of heat required to change the temperature of unit mass of a substance through one degree. Its value is different for different substances. It is denoted by c. It Q J is the amount of heat required to raise the temperature of m kg of a substance by Δt K, then specific heat of this substance.

$$C = \frac{Q}{m\,\Delta t} \text{ J/kg-K} \qquad \because\ Q = mc\Delta t \qquad \text{.....(1.16)}$$

The SI unit of specific heat is J/kg-K. The larger unit is kJ/kg-K.

If the specific heat does not remain constant during heating, it may be assumed that for a small change of temperature dt, specific heat c remains constant. So, the small amount of heat transfer is

$$dQ = mCdt$$

$$\therefore \quad Q = m\int_1^2 Cdt \qquad \text{.....(1.17)}$$

In case of gaseous substance, volume of gas changes with the change in pressure. So heat added to the gas by keeping its volume constant and heat added by keeping the pressure constant would be different. So there will be two different values of specific heat for the gas, one specific heat at constant volume c_v and the other specific heat at constant pressure c_p.

As solids and liquids are generally incompressible, they have single value of specific heat.

The product of mass and specific heat is called the heat capacity of the substance. It is denoted by C.

1.13 Interchange of Heat

When a body at higher temperature comes in contact with another body at lower temperature, there will be an interchange of heat. Heat flows from the body at higher temperature to the body at lower temperature. Heat lost by hot body is equal to heat gained by cold body. There are three modes of heat transfer – conduction, convection and radiation. There will be no interchange of heat if two bodies in contact have equal temperatures.

1.14 Change of State

Matter can exist in three phases – solid, liquid and gas (or vapour). State of the substance can be changed by addition or rejection of heat.

The constant temperature at which solid substance changes to liquid state is called melting point.

When heat is added to solid, first of all, its temperature increases. After melting point is reached, if heat is added further, solid gets converted into liquid at this constant temperature.

Amount of heat required to convert 1 kg of solid into liquid or heat to be rejected to freeze 1 kg of liquid into solid at constant temperature is called latent heat of fusion.

The constant temperature at which liquid changes to vapour is called boiling point or saturation temperature.

If heat is added to liquid, its temperature increases until saturation temperature is reached. At this constant temperature, liquid is converted to vapour by addition of heat.

Amount of heat required to convert 1 kg of liquid into vapour or heat to be rejected to condense 1 kg of vapour into liquid at its saturation temperature is called latent heat of vaporization.

If heat is further supplied to vapour, there will be an increase in its temperature.

1.15 Mechanical Equivalent of Heat

Law of conservation of energy states that energy can neither be created nor destroyed, it can be transformed from one form to another. So, heat energy can be converted into mechanical work.

Thermodynamics is a branch of science which deals with the relation between heat energy and mechanical work. Joule established that heat and work are mutually convertible. This is the statement of First Law of Thermodynamics.

Thus, $W = Q$ when the units of work and heat are same (J) and $W = JQ$ when units of work and heat are different.

Where J (after the name of Joule) is constant and known as mechanical equivalent of heat or Joule's equivalent.

$$J = \frac{W}{Q} \qquad \text{.....(1.18)}$$

When W is in Joule and Q in calorie, J = 4.186 J/cal

1.16 Internal Energy

The amount of heat transferred to a body is not completely converted to work. It is found that when a quantity of heat Q is supplied to a body, some amount of external work W is done due to the expansion and the remaining amount is stored in the body. This stored energy is called internal energy (I.E) of the body, denoted by U. It is neither heat nor work. As it is energy, its unit is Joule.

Thus, $$Q = W + \Delta U \qquad \text{.....(1.19)}$$

Where ΔU is increase (or change) in I.E. of the body. (The body may already have some I.E., so by interaction of Q & W, the change in I.E. is considered).

This relation applies to closed system or non-flow process, where PE and KE are zero.

For a flowing fluid $$Q = W + \Delta E \qquad \text{.....(1.20)}$$

where ΔE is change in total energy of the system, including I.E., PE and KE.

i.e. $E = U + PE + KE$ …..(1.21)

The internal energy per unit mass is denoted by u. Its unit is J/kg or kJ/kg.

Internal energy is the sum of all microscopic forms of energy of a system. It is associated with the molecular structure and activity of the constituent particles of the system. The average velocity and activity of the molecules are proportional to the temperature of the system. Higher the temperature of the body, higher is its I.E. This energy is also associated with intermolecular forces.

1.17 Enthalpy

We have seen that internal energy U is a form of energy stored by a fluid due to supply of heat. The flow work PV is another form of energy possessed by a fluid which is necessary for maintaining the fluid flow. Sum of these two quantities is known as enthalpy of fluid. It is denoted by H. Its unit is Joule.

Thus, $H = U + PV$ …..(1.22)

The enthalpy per unit mass is denoted by h. Unit of h will be J/kg or kJ/kg.

We know that $Q = dU + W$

$= dU + pdV$

When gas is heated at constant pressure from an initial condition 1 to a final condition 2, change in I.E.

$$dU = U_2 - U_1$$

and work done by gas

$$W = PdV$$

$$= P(V_2 - V_1)$$

$$\therefore \quad Q = (U_2 - U_1) + P(V_2 - V_1)$$

$$= (U_2 + PV_2) - (U_1 + PV_1)$$

$$= H_2 - H_1 \qquad \text{…..(1.23)}$$

For a unit mass, $q = h_2 - h_1$ …..(1.24)

Thus, for a constant pressure process, heat supplied to the gas is equal to the change of enthalpy.

1.18 Efficiency

Engine performance is indicated by the term efficiency. Efficiency is denoted by η. The amount of energy supplied to the engine is not completely converted into work. The ratio of work done to the energy supplied is called efficiency.

Thus,

$$\text{efficiency } \eta = \frac{\text{work done by the engine}}{\text{energy supplied}} \qquad .....(1.25)$$

Some of the important engine efficiencies are defined below.

Thermal efficiency: Thermal efficiency of a heat engine is the ratio of heat energy converted to mechanical work to the heat energy supplied to the engine.

$$\text{Thermal efficiency} = \frac{\text{mechanical work done}}{\text{heat energy supplied}} \qquad .....(1.26)$$

Air standard efficiency: It is the thermal efficiency of the engine working with air as a working fluid. This is the ideal efficiency.

Indicated power (ip) of an engine: Power developed in the cylinder of an engine is known as indicated power.

Brake power (bp): Power available for work at the shaft of an engine is known as brake power.

Calorific value of fuel (cv): It is defined as the amount of heat generated by burning of 1 kg of fuel. Its unit is KJ/kg

Thermal efficiency can be based either on ip or bp as shown below.

Indicated thermal efficiency: It is defined as the ratio of ip to heat supplied by fuel.

$$\eta_i = \frac{\text{indicated power, W}}{\text{mass of fuel, kg/s} \times \text{calorific value of fuel, J/kg}}$$

$$= \frac{ip}{m_f \times CV} \qquad .....(1.27)$$

Brake thermal efficiency: It is defined as the ratio of brake power to heat supplied by fuel.

$$\eta_b = \frac{\text{brake power, KW}}{\text{mass of fuel, kg/s} \times \text{calorific value of fuel, KJ/kg}}$$

$$= \frac{bp}{m_f \times CV} \qquad .....(1.28)$$

Mechanical efficiency: It is the ratio of brake power to indicated power

$$\eta_m = \frac{\text{brake power}}{\text{indicated power}}$$

$$= \frac{bp}{ip} \qquad .....(1.29)$$

Relative efficiency: It is the ratio of thermal efficiency of an actual cycle to that of an ideal cycle.

$$\eta_r = \frac{\text{actual thermal efficiency}}{\text{air standard efficiency}} \quad .....(1.30)$$

1.19 Statement of First Law of Thermodynamics

This law may be stated as follows:

(a) "The heat and mechanical work are mutually convertible". According to this law, when a closed system undergoes a thermodynamic cycle, the net heat transfer is equal to net work transfer. In other words, cyclic integral of heat transfer is equal to cyclic integral of work transfer.

$$\oint \delta Q = \oint \delta W \quad .....(1.31)$$

(b) "The energy can neither be created nor destroyed. It can be transferred from one form to another". Thus, 1st law of thermodynamics is the statement of law of conservation of energy. According to this law, when a system undergoes a change of state (or a thermodynamics process), both heat transfer and work transfer take place, the net energy is stored in the system. If Q is the amount of heat transferred and W is the amount of work transferred during the process, the net energy Q – W is stored in the system. This stored energy is known as total energy of the system which includes I.E., PE and KE

Thus $Q - W = \Delta E$

Where $\Delta E = \Delta U + \Delta PE + \Delta KE$ .....(1.32)

For a closed system, change in PE and KE are zero.

So $Q - W = \Delta U$ .....(1.33)

Steady Flow Energy Equation (SFEE)

An open system undergoes a steady flow process as shown in Fig. 1.4. The fluid enters the system at point 1 and leaves the system at point 2. At point 1, various quantities per unit mass are

P_1 = pressure of the fluid

V_1 = volume

v_1 = velocity

z_1 = height from datum

u_1 – internal energy

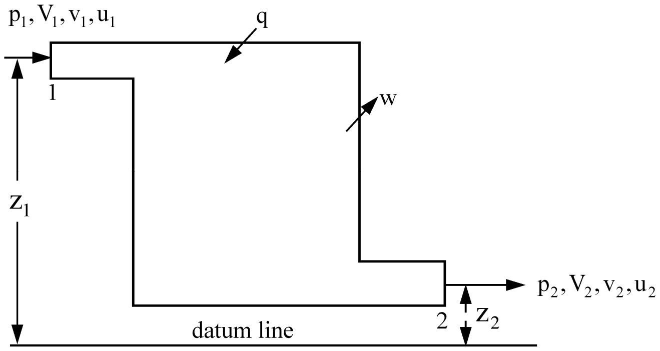


Fig. 1.4 Steady flow process.

P_2, V_2, v_2, z_2 and u_2 are the corresponding quantities at point 2.

q = heat transferred to the system

W = work done by the system

At 1, Flow work = $p_1 V_1$

Kinetic energy = $\frac{1}{2}v_1^2$

Potential energy = gz_1

So, the total energy entering the system at 1

$$= u_1 + P_1V_1 + \frac{1}{2}v_1^2 + gz_1 + q$$

Total energy leaving the system from 2

$$= u_2 + P_2V_2 + \frac{1}{2}v_2^2 + gz_2 + w$$

According to law of conservation of energy,

Total energy entering the system = total energy leaving the system

$$\therefore \quad u_1 + p_1V_1 + \frac{1}{2}v_1^2 + gz_1 + q = u_2 + p_2V_2 + \frac{1}{2}v_2^2 + gz_2 + w$$

$$\therefore \quad h_1 + \frac{1}{2}v_1^2 + gz_1 + q = h_2 + \frac{1}{2}v_2^2 + gz_2 + w \qquad \text{.....(1.34)}$$

This equation is known as SFEE. Further, it may be simplified to

$$q = w + (h_2 - h_1) + \frac{1}{2}(v_2^2 - v_1^2) + g(z_2 - z_1) \qquad \text{.....(1.35)}$$

1.20 Statement of Second Law of Thermodynamics

The 1st law states that heat and work are mutually convertible. According to this law, in a cycle, work is completely converted into heat and vice versa. But we know that heat is not completely converted into work

We will study two statements of second law of thermodynamics.

1. Kelvin-Planck statement 2. Clausius statement.

1. ***Kelvin-Planck statement***

It is impossible to construct an engine working on a cyclic process, whose sole effect is to convert heat energy from a single reservoir into an equivalent amount of work. In other words, no actual heat engine can convert whole of the heat supplied to it into mechanical work. It means that to produce net work in a cycle, certain amount of heat has to be rejected to a lower temperature body. See Fig. 1.5. The body at higher temperature T_1 from which heat is extracted is known as source. The body at lower temperature T_2 to which heat is rejected is called sink.

$$W < Q_1, \quad T_1 > T_2, \; Q_2 > 0$$

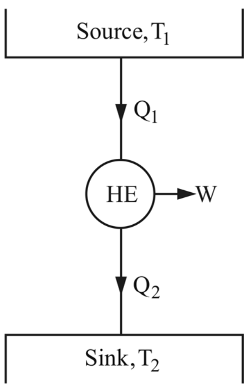


Fig. 1.5 Heat engine operating between two temperatures.

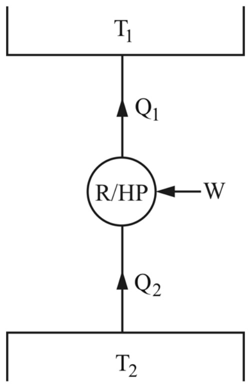


Fig. 1.6 Work has to supply to transfer heat from a cold to hot body.

2. ***Clausius statement***

It is impossible to construct a device, working in a cyclic process, to transfer heat from a body at lower temperature to a body at higher temperature without the aid of an external agency. It means that heat cannot flow itself from a cold body to a hot body without expenditure of mechanical work. Refrigerator and a heat pump, while operating in a cyclic process, can transfer heat from a cold body to hot body. They require an input work for this purpose as shown in Fig. 1.6.

The two statements of 2nd law of thermodynamics mentioned above, are equivalent.

Solved Problems

1. The pressure of steam inside a boiler is recorded by a pressure gauge which shows 1.2×10^6 N/m^2. If the barometer reads the atmospheric pressure as 770 mm of Hg, find the absolute pressure of steam inside the boiler in N/m^2, kPa and bar.

Atmospheric pressure = 760 mm of Hg = 1.01325×10^5 N/m^2

Solution: So, 770 mm of Hg = $\frac{1.01325 \times 10^5 \times 770}{760}$ N/m^2

$= 1.02641 \times 10^5$ N/m^2

$= 0.1026 \times 10^6$ N/m^2

This is atmospheric pressure measured by barometer.

Absolute pressure = gauge pressure + atmospheric pressure

$= 1.2 \times 10^6 + 0.1026 \times 10^6$ N/m^2

$= 1.3026 \times 10^6$ N/m^2

$= 1.3026 \times 10^6$ Pa

= 1302.6 kPa

= 13.026 bar

2. The density of mercury is 13600 kg/m^3. Calculate the pressure due to 600 mm of Hg in kPa and bar.

Solution: Pressure $P = \rho g h$

$= 13600 \times 9.81 \times \frac{600}{1000}$ N/m^2

$= 80.05 \times 10^3$ N/m^2

$= 80.05 \times 10^3$ Pa

= 80.05 kPa

= 0.8005 bar

3. The temperature of 4.5 kg of water is raised from 15 ^{o}C to 100 ^{o}C at constant atmospheric pressure. Determine the heat transferred. Specific heat of water = 4.186 kJ/kg-K.

Solution: Heat transferred $= mc\,(t_2 - t_1)$

$= 4.5 \times 4.186 \times (100 - 15)$

= 1601 kJ

4. In a thermal power plant 220000 kg of coal is burnt per hour. The calorific value of coal is 30000 kJ/kg. The efficiency of conversion is 30%. Determine the power developed.

Solution:

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{W}{Q}$$

$$\therefore \quad \eta = \frac{W}{m_f \times CV} \qquad m_f \text{ should be taken in kg/s}$$

$$\therefore \quad W = \eta \times m_f \times CV$$

$$= 0.3 \times \frac{220000}{3600} \times 30000 \ \frac{kJ}{s}$$

$$= 550 \times 10^3 \text{ kW}$$

$$\mathbf{= 550\ MW}$$

5. An engine has thermal efficiency of 30%. The engine rejects 1000 MJ/hr. Calorific value of fuel is 30000 kJ/kg. Determine power output and fuel consumed by the engine.

Solution:

$$\eta = \frac{W}{Q_1} \qquad \text{Work done = heat supplied – heat rejected}$$

$$= Q_1 - Q_2$$

$$\therefore \quad \eta = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1}$$

$$\therefore \quad 0.3 = 1 - \frac{1000}{Q_1}$$

$$\therefore \quad \frac{1000}{Q_1} = 0.7 \qquad \therefore Q_1 = \frac{1000}{0.7} = 1428.6 \text{ MJ/hr}$$

Now $W = Q_1 - Q_2$

$$= 1428.6 - 1000$$

$$= 428.6 \text{ MJ/hr}$$

$$= \frac{428.6 \times 10^3}{3600} \text{ kJ/s}$$

$$\mathbf{= 119\ kW}$$

$Q_1 = m_f \times CV$

$\therefore$ $1428.6 \text{ MJ/hr} = m_f \dfrac{\text{kg}}{\text{hr}} \times 30 \dfrac{\text{MJ}}{\text{kg}}$

$\therefore$ $\mathbf{m_f = 47.62 \text{ kg/hr}}$

6. A power station has an output of 800 MW and thermal efficiency is 28%. Determine the coal consumed in tonne/hr. Calorific value of coal is 31 MJ/kg.

Solution: $\eta = \dfrac{W}{Q} = \dfrac{W}{m_f \times CV}$

$\therefore$ $m_f = \dfrac{W}{\eta \times CV} = \dfrac{800 \text{ MW}}{0.28 \times 31 \text{ MJ/kg}}$

$= 92.166 \text{ kg/s}$

$= \dfrac{92.166 \times 3600}{1000}$ tonne/hr

= 331.8 tonne/hr

7. The work produced in an engine cylinder in 6 minutes is 2870 kJ and the work done against the engine brake in 10 minutes is 3800 kJ. Find (i) Power produced in the cylinder (ii) Power delivered to the brake.

Solution: Power produced $= \dfrac{2870}{6 \times 60}$ kJ/s

= 7.97 kW

Power delivered to brake $= \dfrac{3800}{10 \times 60}$ kJ/s

= 6.33 kW

8. A hydraulic engine receives 25000 kg of water per minute and develops 80 kW. Find the effective pressure exerted on the piston of the engine.

Solution: 1 kg of water = 1 litre of water = 10^{-3} m^3

$\therefore$ 25000 kg of water $= 25000 \times 10^{-3}$ m^3

$= 25$ m^3 of water

The volume flow rate of water $= 25$ m^3/min

$= \dfrac{25}{60}$ m^3/s

Work developed/sec = P × V

$\therefore \qquad 80\text{kW} = P\frac{\text{kN}}{\text{m}^2} \times \frac{25}{60}\frac{\text{m}^3}{\text{s}}$

$\therefore \qquad P = \frac{80 \times 60}{25}\frac{\text{kN}}{\text{m}^2}$

$= \mathbf{192\ kN/m^2}$

9. In a non-flow process there is a heat loss of 1055 kJ and an internal energy increase 210 kJ. How much work is done?

For a non-flow process, $Q = W + \Delta U$

Solution: Here, it is heat loss, so Q is negative

$\therefore \qquad -1055 = W + 210$

$\therefore \qquad \mathbf{W = -1265\ kJ}$

Work is negative, so work is spent here.

10. A cycle consists of four processes and the heat transfer during the processes were +84 kJ, –8.4 kJ, –21 kJ and +4.2 kJ. Calculate the net work done during the cycle.

Solution: Heat transfer during the cycle is

$$\oint dQ = 84 - 8.4 - 21 + 4.2\ \text{kJ}$$

$$= 58.8\ \text{kJ}$$

Now $\qquad \oint dW = \oint dQ$

$\therefore \qquad \oint \mathbf{dW = 58.8\ kJ}$

11. In a system 45 kg/s of working fluid enters with 10 m/s velocity and leaves with 19 m/s velocity. The system receive 46 kJ/s of heat and does 15 kW of work. The outlet is 30 m above the inlet. Find change in specific enthalpy of working fluid.

Solution: SFEE for unit mass flow rate is

$$h_1 + \frac{1}{2}v_1^2 + gz_1 + \frac{Q}{m} = h_2 + \frac{1}{2}v_2^2 + gz_2 + \frac{W}{m}$$

$\therefore \qquad h_2 - h_1 = \frac{1}{2}\left(v_1^2 - v_2^2\right) + g\left(z_1 - z_2\right) + \frac{Q}{m} - \frac{W}{m}$

$$= \frac{1}{2}\frac{(10^2 - 19^2)}{1000} + 9.8 \times \left(\frac{-30}{1000}\right) + \frac{46}{45} - \frac{15}{45}$$

$= -0.130 - 0.294 + 1.022 - 0.333$ kJ/kg

$= 1.022 - 0.757$

$= \mathbf{0.265\ kJ/kg}$

Objective Type Questions

1. Which of the following is a renewable source of energy?

   (a) Solar (b) Natural gas (c) Coal (d) Petroleum

2. Which of the following is not the unit of pressure?

   (a) Bar (b) Newton (c) Pascal (d) mm of mercury

3. Which is the unit of pressure?

   (a) Newton (b) Watt (c) Joule (d) N/m^2

4. Barometer is used to measure

   (a) Atmospheric pressure (b) Temperature

   (c) Work done (d) Power

5. 1 bar is equal to

   (a) 1 N/m^2 (b) 760 mm of Hg (c) 10^5 Pascal (d) 100 Pascal

6. Unit of work is

   (a) Newton (b) N-m (c) Bar (d) Watt

7. 1 hp is equal to

   (a) 750 W (b) 50 W (c) 735.5 W (d) 735.5 kW

8. kWh is the unit of

   (a) Power (b) Force (c) Pressure (d) Energy

9. 1 kWh is equal to

   (a) 36×10^5 J (b) 36×10^5 kJ (c) 10^5 Joule (d) 1 Joule

10. Relation between K and celsius scales of temperature is

    (a) 1 ^oC = 1 K (b) K = ^oC + 273 (c) ^oC = K + 273 (d) 1K = 100 ^oC

11. 1 kcal is equal to

    (a) 4.186 J (b) 4186 kJ (c) 4186 J/s (d) 4186 J

12. 1st law of thermodynamics deals with

    (a) Conservation of momentum (b) Conservation of heat

    (c) Conservation of energy (d) Conservation of mass

13. 1st law of thermodynamics defines

    (a) Work (b) Internal energy (c) Heat (d) Entropy

Answers to Objective Type Questions

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

Short Questions

1. What is a prime mover?
2. Which are the different sources of energy?
3. Define

   (a) Force (b) Weight (c) Pressure (d) Work (e) Power (f) ip (g) bp (h) Energy (i) PE (j) KE (k) Temperature (l) Specific heat (m) Heat capacity (n) Melting point (o) Latent heat of fusion (p) Saturation temperature (q) Latent heat of vaporization (r) Mechanical equivalent of heat (s) Internal energy (t) Enthalpy (u) Thermal efficiency (v) Air standard efficiency (w) Indicated thermal efficiency (x) Brake thermal efficiency (y) Mechanical efficiency (z) Relative efficiency
4. Give SI units of following quantities

   (a) Force (b) Pressure (c) Work (d) Power (e) Energy (f) Temperature (g) Heat (h) Specific heat (i) Latent heat (j) Internal energy (k) Enthalpy (l) Efficiency (m) Calorific value
5. Give different units of pressure.
6. What is the magnitude of atmospheric pressure?

7. Give names of pressure measuring instruments
8. Give relation between absolute pressure and gauge pressure.
9. What is flow work?
10. What is the difference between heat and temperature?
11. Give names of different units of heat. Write relation between them.
12. What is the old name of Celsius scale?
13. Why has gas two specific heats?
14. Which are the different modes of heat transfer?
15. What is the law of conservation of energy?
16. What is Thermodynamics?
17. What is the value of J when units of heat and work are same?
18. Why efficiency of an engine is less than 100%?
19. What is calorific value of fuel?
20. Can heat be completely converted to work?
21. Write SFEE.

Long Questions

1. Write short notes on

   (a) Sources of energy (b) Types of prime movers (c) Temperature (d) Specific heat (e) Internal energy (f) 1^{st} law of Thermodynamics
2. Show that area of P.V diagram represents work done.
3. Explain change of state of a substance.
4. Show that for a constant pressure process, heat supplied to gas is equal to change of enthalpy.
5. Explain Kelvin-Planck statement of 2^{nd} law of Thermodynamics.
6. Explain Clausius statement of 2^{nd} law of Thermodynamics.

Exercises

1. The pressure of steam inside the boiler, as measured by pressure gauge is 1×10^6 N/m^2. The barometric pressure of the Atmosphere is 765 mm of mercury. Find the absolute pressure of steam in N/m^2, kPa, bar and N/mm^2.

   [1.102×10^6 N/m^2, 1102 kPa, 11.02 bar, 1.102 N/mm^2]

2. Certain quantity of air undergoes a change of state in such a way that 50 kJ of heat is transferred to the system. For this change of state, work produced is 40 kJ. Calculate the change in its internal energy. Assume that the process is non-flow.

   [10 kJ]

3. A steam engine piston having an area of 160 cm^2 moves a distance of 200 mm inside the cylinder. Find the amount of work done if the pressure exerted on the piston is 70 kN/m^2

   [224 J]

4. A fluid in a cylinder is at a pressure of 7 bar. It is expanded at constant pressure from 0.3 m^3 to 1.5 m^3. Calculate the work done.

   [840 kJ]

5. Find the theoretical power developed by an water wheel if it receives 500 kg of water per sec at a pressure of 1.5 bar.

   [75 kW]

6. 10 kg of steel, having a specific heat of 450 J/kg.K is heated from 20 ^oC to 100 ^oC. How much heat is required?

   [360 kJ]

7. A steam plant uses 3 tonne of coal in one hour. The steam is fed to turbine. Output of turbine is 4 MW. Calorific value of coal is 30 MJ/kg. Calculate the thermal efficiency of the plant.

   [16 %]

8. 2000 m^3 of water is to be delivered in 30 minutes to a vertical distance of 30 m. Determine the power required.

   [327 kW]

9. An engine rejects 1260 MJ/hr when running at a efficiency of 22%. The calorific value of fuel used is 42 MJ/kg. Determine the power output of the engine and mass of fuel used in one hour.

[98.72 kW, 38.5 kg/hr]

10. A gas enters a system at an initial pressure of 0.5 MPa and flow rate of 0.15 m^3/s and leaves at a pressure of 0.95 MPa and flow rate of 0.09 m^3/s. During the passage through the system, the increase in internal energy is 22 kJ/s. Find the change in enthalpy of the medium.

[32.5 kJ]

11. A system undergoes a cycle composed of four processes. Heat transfer in these processes are 400 kJ, –365 kJ, –200 kJ and 250 kJ. The respective work transfers are 140 kJ, 0, –55 kJ and 0. Is the data consistent with 1^{st} law of Thermodynamics?

[Yes]