1.1 INTRODUCTION

A cycle is defined as sequence of processes which end in the same final state of the substance as the initial. The heat engines are devices which produce work by using heat from a reservoir and rejecting heat to another constant temperature reservoir called heat sink. Perhaps in earlier days some heat engines were developed which directly used the heat from sun, hitherto all engines have been using heat produced from combustion of fuel. Apart from heat source the engine has to have some working fluid that will absorb and reject heat and undergo such processes as expansion and compression. For theoretical study of cycles for engines it is assumed that some working fluid remains in the machine and undergoes different processes over and over again. A number of standard cycles, consisting of well known processes have been developed. We will study a few of them.

Objectives

After studying this unit, you should be able to

- know Carnot cycles,
- explain Otto cycle,
- describe Diesel cycle,
- appreciate Dual combustion cycle,
- define steam cycle, and
- explain modified Rankine cycle.

1.2 CARNOT CYCLE

Carnot was the first to study the performance of heat engine. Here, we describe the cycle as shown in Figure 1.1. The engine is made of a piston in a cylinder again shown in the same Figure. The cycle consists of four processes.

expansion

xpansion

compression

4-1-adiabatic compression

During 1-2 and 2-3, work is performed by gas (air) on the piston, whereas during 3-4 and 4-1, work is performed on the gas by the piston.

At 1, a volume of air equal to V_1 is contained in confined space between the piston and cylinder walls. Also assume the mass of the air is m = 1 kg.

During isothermal expansion 1-2, a heat source (reservoir) is brought in contact with the cylinder end and since expansion is at constant temperature, entire heat transferred from hot body to the air is converted into work without any change in the internal energy.

Thus, $$W_{12} = Q_{12} = p_1 V_1 \ln \frac{V_2}{V_1} = R T_1 \ln \frac{V_2}{V_1} \qquad \ldots \text{(i)}$$

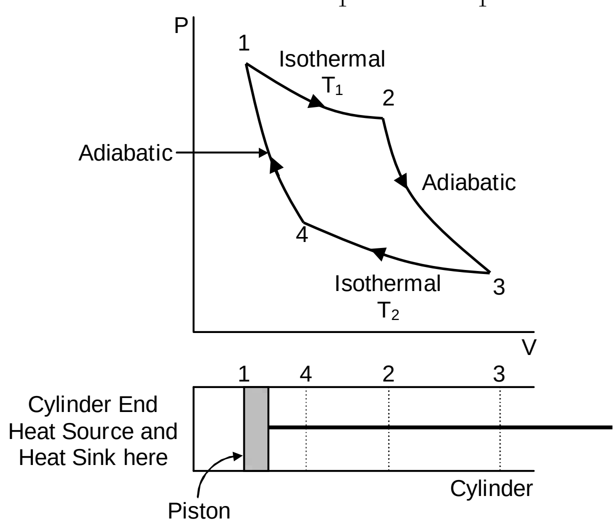

Figure 1.1 : Carnot Cycle

Similarly, at point 3, a heat sink at T_3 is brought in contact with the cylinder end and heat is transferred at T_3 to the sink from air. Work is performed on the air by the piston and is entirely equal to heat transferred to the sink without any change in the internal energy.

Thus $$W_{34} = Q_{34} = p_3 V_3 \ln \frac{V_3}{V_4} = R T_2 \ln \frac{V_3}{V_4} \qquad \ldots \text{(ii)}$$

During adiabatic expansion 2-3 no heat is transferred, so Q_{23} = 0.

The internal energy changes to perform work on piston.

$$W_{23} = \frac{p_2 V_2 - p_3 V_3}{\gamma - 1} = \frac{R}{\gamma - 1} (T_2 - T_3) \qquad \ldots \text{(iii)}$$

During adiabatic compression 4-1, work is done upon air, no heat is transferred so Q_{41} = 0 and

$$W_{41} = \frac{p_1 V_1 - p_4 V_4}{\gamma - 1} = \frac{R}{\gamma - 1} (T_1 - T_4) \qquad \ldots \text{(iv)}$$

ne by the piston ï Work done on the

$$\ldots_2 \ln \frac{V_3}{V_4} - \frac{R}{\gamma - 1} (T_1 - T_4)$$

For adiabatic expansion

$$\frac{T_1}{T_2} = \left(\frac{V_3}{V_2}\right)^{\gamma - 1}$$

For adiabatic compression

$$\frac{T_1}{T_2} = \left(\frac{V_4}{V_1}\right)^{\gamma - 1}$$

$\therefore$ $$\frac{V_3}{V_2} = \frac{V_4}{V_1}$$

or $$\frac{V_3}{V_4} = \frac{V_2}{V_1}$$

Also note that $T_1 = T_2$ and $T_3 = T_4$

$$W = RT_1 \ln \frac{V_2}{V_1} - RT_3 \ln \frac{V_2}{V_1} + \frac{R}{\gamma - 1} (T_2 - T_3) - \frac{R}{\gamma - 1} (T_2 - T_3)$$

$$= R \ln \frac{V_2}{V_1} (T_1 - T_3) \quad \ldots$$

(v)

The heat received by the engine

$$= Q_{12} = RT_1 \ln \frac{V_2}{V_1} \quad \ldots$$

(vi)

The efficiency of the engine is defined as the ratio of work obtained to heat supplied

$\therefore$ $$\eta = \frac{R \ln \left(\frac{V_2}{V_1}\right) (T_1 - T_3)}{R \ln \left(\frac{V_2}{V_1}\right) T_1}$$

or $$\eta = \frac{T_1 - T_3}{T_1} \quad \ldots$$

(1.1)

Note that here T_1 is the temperature of hot reservoir and T_3 is the temperature of cold reservoir of heat. Heat is abstracted by the engine from hot reservoir and rejected to cold reservoir. The efficiency of the Carnot cycle is highest.

1.3 OTTO CYCLE

The most practical air cycle on which petrol engines work is the Otto cycle comprising four processes, viz.

1-2 Adiabatic expansion

2-3 Constant volume heat rejection

c compression

volume heat addition (Figure 1.2).

done on the piston or by the piston during constant volume
ss of air in the engine is 1 kg.

Heat rejected by the air in the engine during the process 2-3

$$Q_{23} = C_v (T_2 - T_3)$$

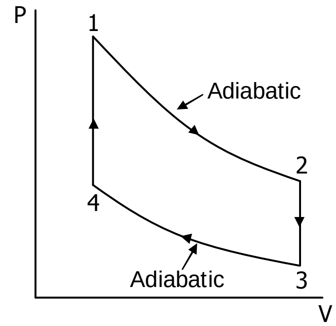

Figure 1.2 : Otto Cycle

Heat received during the process 4-1

$$Q_{41} = C_v (T_1 - T_4)$$

Heat rejection during the process 2-3

$$Q_{23} = C_v (T_2 - T_3)$$

$$\therefore \qquad W = Q_{41} - Q_{23}$$

$$\therefore \qquad \eta = \frac{Q_{41} - Q_{23}}{Q_{41}} = \frac{T_1 - T_4 - T_2 + T_3}{T_1 - T_4} = 1 - \frac{T_2 - T_3}{T_1 - T_4}$$

Note $\frac{V_2}{V_1} = \frac{V_3}{V_4} = r$, where r is called compression ratio. It may also be pointed out here that $V_1 = V_4$ is called the clearance volume

$$\frac{p_1 V_1}{p_2 V_2} = \frac{T_1}{T_2} \text{ from gas equation}$$

Also for adiabatic expansion

$$\frac{p_1}{p_2} = \left(\frac{V_2}{V_1}\right)^{\gamma}$$

$$\therefore \qquad \frac{T_1}{T_2} = \left(\frac{V_1}{V_2}\right)^{1-\gamma} = \left(\frac{V_2}{V_1}\right)^{\gamma - 1} = (r)^{\gamma - 1}$$

Similarly $\qquad \frac{T_4}{T_3} = (r)^{\gamma - 1}$

$$\therefore \qquad \frac{T_1}{T_2} = \frac{T_4}{T_3}$$

or $\qquad \frac{T_1}{T_4} = \frac{T_2}{T_3}$

or $$\eta = 1 - \frac{1}{(r)^{\gamma - 1}}$$ . .

(1.2)

From above expression it can be concluded that efficiency of Otto cycle increases with compression ratio *r*. A compression ratio in the vicinity of 7-8 is commonly used in petrol engines.

Example 1.1

Calculate efficiencies of a Carnot cycle for compression ratios of 7, 8, 9 and 10 for air as working fluid.

Solution

Use γ = 1.4 for air,

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

r	$r^{\gamma-1}$	$1 / (r)^{\gamma-1}$	$\eta = 1 - 1/ (r)^{\gamma-1}$
7	2.18	0.46	0.54
8	2.30	0.435	0.565
9	2.41	0.415	0.584
10	2.51	0.400	0.600

1.4 DIESEL CYCLE

This cycle is shown in Figure 1.3. Diesel engines using diesel fuel work on this cycle. The main difference lies in the fact that at the end of compression process sufficiently high temperature is obtained and fuel which is injected at this point ignites without any aid. In case of Otto cycle, a spark is needed to cause ignition of the fuel which is present during process of compression.

In this cycle, the heat is transferred to fuel during constant pressure process when fuel is injected. The fuel burns during constant pressure process only. The gas (air) then expands adiabatically followed by heat rejection which occurs at constant volume. The air is then compressed adiabatically.

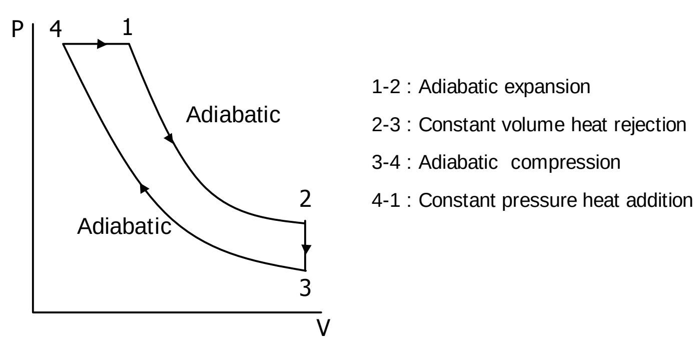

Figure 1.3 : Diesel Cycle

$$, \eta = \frac{\text{Work done}}{\text{Heat added}} = \frac{\text{Head added} - \text{Heat rejected}}{\text{Heat added}}$$

$$\eta = \frac{Q_{41} - Q_{23}}{Q_{41}}$$

$$= \frac{C_p \,(T_1 - T_4) - C_v \,(T_2 - T_3)}{C_p \,(T_1 - T_4)}$$

$$= 1 - \frac{C_v \,(T_2 - T_3)}{C_p \,(T_1 - T_4)} = 1 - \frac{T_3 \left(\frac{T_2}{T_3} - 1 \right)}{\gamma \, T_4 \left(\frac{T_1}{T_4} - 1 \right)}$$

It may be noted that in case of diesel cycle the compression ratio is greater than expansion ratio.

For adiabatic compression, $\frac{T_4}{T_3} = \left(\frac{V_3}{V_4} \right)^{\gamma - 1}$

For adiabatic expansion, $\frac{T_1}{T_2} = \left(\frac{V_2}{V_1} \right)^{\gamma - 1}$

Calling $V_4 = 1$, $V_1 = \rho$, the cut off ratio and $V_2 = V_3 = r$ = compression ratio

$$\frac{V_3}{V_4} = r, \quad \frac{V_2}{V_1} = \left(\frac{r}{\rho} \right)$$

For constant pressure process 4-1, $p_4 = p_1$

$$\therefore \qquad \frac{p_1 \, V_1}{T_1} = \frac{p_4 \, V_4}{T_4}$$

or $$\frac{\rho}{T_1} = \frac{1}{T_4}$$

or $$\frac{T_1}{T_4} = \rho$$

For constant volume process, 2-3

$$\frac{p_2 \, V_2}{T_2} = \frac{p_3 \, V_3}{T_3}$$

or $$\frac{p_2}{p_3} = \frac{T_2}{T_3}$$

For adiabatic process 1-2,

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1} \right)^{\gamma - 1} = \left(\frac{r}{\rho} \right)^{\gamma - 1}$$

For adiabatic process 3-4,

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4} \right)^{\gamma - 1} = (r)^{\gamma - 1}$$

$$p_2 (r)^{\gamma} = p_1 (\rho)^{\gamma}$$

$$= p_4$$

$$\therefore \quad \frac{p_2}{p_3} = \frac{p_1}{p_4} (\rho)^{\gamma} = (\rho)^{\gamma} = \frac{T_2}{T_3}$$

Substituting for $\frac{T_2}{T_3}$, $\frac{T_1}{T_4}$ and $\frac{T_3}{T_4}$ in expression for η

$$\eta = 1 - \frac{1}{\gamma (r)^{\gamma - 1}} \times \frac{\rho^{\gamma} - 1}{\rho - 1} \qquad \ldots (1.3)$$

Diesel cycle normally has much higher compression ratio. For same compression ratio the efficiency decreases for increasing cut off ratio.

Example 1.2

Calculate the efficiency of a diesel cycle for which compression ratio is 14 and cut off ratio is 2. What will be the efficiency if cut off ratio is increased to 3. Given $\gamma = 1.4$.

Solution

Use $r = 14$ and $\rho = 2$ with $\gamma = 1.4$ in Eq. (1.3).

$$\eta = 1 - \frac{1}{1.4\,(14)^{0.4}} \times \frac{2^{1.4} - 1}{2 - 1}$$

$$= 1 - \frac{1}{4.02} \times \frac{1.64}{1} = 0.59$$

or $\quad \eta = 59\%. \qquad \ldots$ (i)

Use $r = 14$ and $\rho = 3$ with $\gamma = 1.4$ in Eq. (1.3)

$$\eta = 1 - \frac{1}{1.4\,(14)^{0.4}} \frac{3^{1.4} - 1}{3 - 1}$$

$$= 1 - \frac{1}{4.02} \times \frac{3.655}{2} = 0.545$$

or $\quad \eta = 54.5\ \% \qquad \ldots$ (ii)

1.5 DUAL COMBUSTION CYCLE

It is more practical that heat is supplied partly during constant volume and partly during constant pressure processes. Such a cycle, shown in Figure 1.4, is called dual combustion cycle.

Heat addition during 4-5 (constant volume) and 5-1 (constant pressure) processes.

Heat rejection during 2-3 (constant volume process).

$$V_5 = 1, \; \frac{P_5}{P_4} = \alpha, \; \frac{V_3}{V_4} = r, \; \frac{V_1}{V_5} = \rho$$

It can be shown that efficiency of dual combustion cycle is

$$= 1 - \frac{1}{r^{\gamma-1}} \left[\frac{\alpha \, \rho^{\gamma-1}}{(\alpha - 1) + \alpha^{\gamma} \, (\rho - 1)} \right] \quad \ldots$$

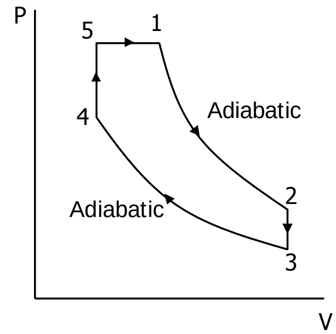

Figure 1.4 : Dual Combustion Cycle

There are many other cycles that are used in practice but we do not deal with them since scope of the text is limited. Stirling cycle, Ericsson cycle and Brayton cycle are just mentioned here. Another important cycle used with steam as working medium will be discussed.

1.6 STEAM CYCLE

The cycles which use air as medium is known as *air standard cycles*. They are used in internal combustion engines like petrol and diesel engines and in gas turbine. They are also referred to as *power cycles*.

Apart from internal combustion engines and gas turbines in which heat is provided by burning of fuel inside the body of engine or very close to turbine in combuster, a very common and popular source of power is steam which was earlier used in steam engines and turbine but former has been almost phased out because of its lower efficiency. Steam turbine still remains the major source of power in large capacity in the range of few hundred MW. The present day is seeing the advent of combined cycle power plants in which both gas and steam turbines are used together.

The use of steam is based upon large latent heat which water absorbs when changes into steam. Steam is produced at high pressure where its boiling point is high but when it expands in the turbine its pressure reduces continuously and its boiling point simultaneously reduces so it remains vapour until the end of expansion to very low pressure. Thus, enough expansion work is obtained from steam.

The total cycle consists of water converting into steam, expansion of steam and steam condensing into water.

The raising of steam requires a separate system called boiler which is a strong vessel with a series of tubes. The water may evaporate in tube or outside the tube. In first case hot gases pass outside the tubes and second case they pass inside the tube. The steam is stored in the vessel from where it passes into turbine. The hot gases are produced by burning fuel in the furnace which in earlier days used to be mainly coal but now-a-days liquid fuel, gaseous fuel and pulverized coal are being preferred. The steam after passing through turbine passes into condenser where it condenses into water at very low pressure. This water through a pump is injected into the vessel (drum of the boiler) and thus the cycle repeats.

The cycle on which the above system works is named *Rankine cycle* but before we go for its description let us get familiar with some of the properties of water (steam) which is known as pure substance because no impurities in it are permitted.

oiler, the steam engines and turbines have
n engines. This term, however, is not

Steam is a state of water, partially or fully vapourized. If steam contains water particles it is *wet*. A *saturated* steam does not contain water particles. Water vapourises at *saturation temperature*. There is a unique saturation temperature at each pressure. The amount of heat absorbed by water anywhere between 0°C to its saturation temperature is called *Sensible heat* (h_f). This is also known as *enthalpy of saturation*. The heat absorbed by water at saturation temperature is called *latent heat* (L). The process of evaporation will continue at constant temperature for a given pressure until whole of water is converted into steam. The steam at the saturation temperature is known as saturated steam. If water particles to the extent of w kg are present along with M_s kg of saturated steam then the quality of steam (or dryness fraction), x, is defined as

$$x = \frac{M_s}{M_s + w} \quad \ldots (1.5)$$

The enthalpy of wet steam is given by

$$h = h_f + xL \quad \ldots (1.6)$$

The enthalpy of saturated steam ($x = 1$)

$$h_{sat} = h_f + L \quad \ldots (1.7)$$

If steam continues to be heated from its saturation state then it absorbs heat and gets superheated. The superheating is done at constant pressure. The enthalpy of superheated steam is

$$h_{\text{sup}} = h_f + L + C_p (T_{\text{sup}} - T) \quad \ldots (1.8)$$

C_p is the specific heat at constant pressure.

Volume of steam is much larger than the volume of water from which the steam is obtained. The latter is negligible. Specific volume of wet steam and saturated steam are correlated as

$$v_{\text{sw}} = x\, v_{\text{sat}}$$

v_{sw} is volume of 1 kg of wet steam and v_{sat} is volume of 1 kg of saturated steam. The specific volumes of superheated and saturated steam are related as

$$v_{\text{sup}} = v_{\text{sat}} \frac{T_{\text{sup}}}{T_{\text{sat}}} \quad \ldots (1.9)$$

since superheating is a constant pressure process.

A pressure volume diagram of Figure 1.5 illustrates water-vapour phases.

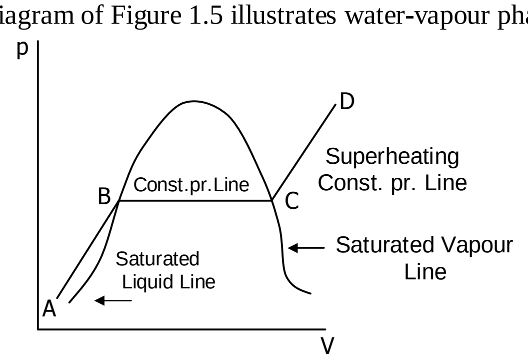

Figure 1.5 : Pressure-Volume Diagram

Steam can be expanded in all those manners as described in case of gas. One process which was not described earlier is very common in steam practice and that is *throttling*. It can be understood as expansion through a minute aperture like opening of a valve. In this process, neither the work is done ($W = 0$) nor the heat is exchanged ($Q = 0$). Due to drop in pressure the gas or steam comes out with a great velocity. But due to friction at the exit heat is added and thus kinetic energy is converted into heat. This type of expansion is very common with steam as it is produced at a much higher pressure and it may be necessary to use it at a lower pressure. The steam is often throttled to much larger volume and lower pressure in which process steam gets superheated even if it is wet.

1.7 RANKINE CYCLE

As was stated earlier a Rankine cycle consists of following processes :

- 1-2 : Pumping water from condenser to boiler, it requires work but the work is very small in comparison of work and heat in other processes, hence negligible.
- 2-3 : Constant pressure heat addition in the boiler, it can heat water into wet, saturated or superheated steam.
- 3-4 : Expansion of steam in an engine or turbine, converting heat into work, normally an adiabatic process.
- 4-1 : Condensing steam into water at low pressure which is the exit pressure of engine or turbine.

The work is obtained from expansion process 3-4 and heat is supplied during heating process 2-3. The pumping work during 1-2 is negligible. The heat is rejected during condensation process 4-1.

The cycle is represented in Figure 1.6.

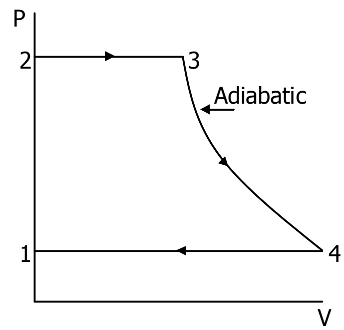

Figure 1.6 : Rankine Cycle

$$W = h_3 - h_4$$

$$Q = h_3 - h_2$$

$$\eta = \frac{W}{Q} = \frac{h_3 - h_4}{h_3 - h_2}$$

$(h_2 - h_1)$ may be very small.

e cycle is shown in Figure 1.7.

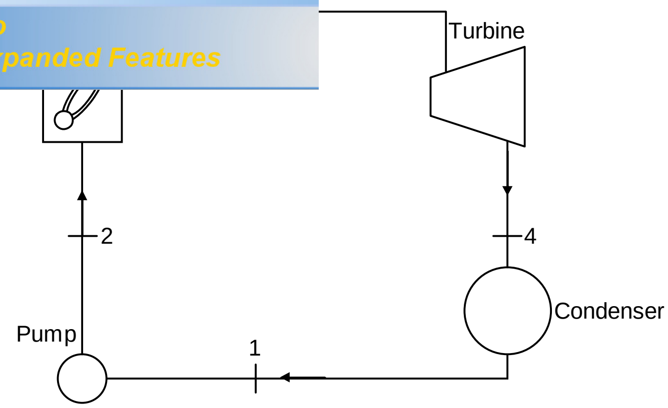

Figure 1.7 : Block Diagram of Rankine Cycle

1.8 MODIFIED RANKINE CYCLE

In a modified Rankine cycle, steam is not allowed to expand fully to point *d* as shown in Figure 1.5 as it takes a long piston stroke, or several stages in the turbine. Steam is cut off at some point '*D*'. Before *D*, the steam passes into condenser at constant volume. It reduces the work but saves condenser space considerably.

Example 1.3

In a Rankine cycle, steam leaves the boiler and enters the turbine at 4 MPa and 400°C. It is expanded in two stages to 10 kPa.

At p_3 = 4 MPa and 400°C, h_3 = 3214.3 kJ/kg (Enthalpy of superheated steam)

At p_4 = 10 kPa and exhaust temp., h_4 = 2135.7 kJ/kg

At $p_2 = p_3$, h_{2f} = 1087.3 kJ/kg

At $p_1 = p_4$, h_{1f} = 194 kJ/kg

Calculate work done in the cycle and its efficiency.

Solution

Refer Figure 1.6

Work done, $W = (h_3 - h_4)$

$= (3214.3 - 2135)$

Heat supplied $= h_3 - h_2$

$= 3214.3 - 194$

$$\therefore \qquad \eta = \frac{3214.3 - 2135}{3214.3 - 194}$$

$$= \frac{1079.3}{3020.3}$$

or $\qquad \eta = 0.357$ or 35.7 %.

1.9 CYCLES IN ENGINES

Standard air cycles were discussed in last unit. Out of these the Carnot cycle is practically not used. It involves an isothermal process followed by an adiabatic process in one stroke

...al process is very slow whereas adiabatic is very fast and practically ... the speed of the piston in a single stroke.

...ycles are practically followed in petrol and diesel engines ... gas engines and paraffin engines which work on Otto cycle. Diesel engine also works on dual combustion cycle. The paraffin engine can also work on Diesel cycle.

It may be understood that for same compression ratio Otto cycle is more efficient than Diesel cycle. Even otherwise, when diesel cycle works with a higher compression ratio this cycle is not as efficient as Otto cycle. It is because burning of fuel at constant pressure is less efficient than burning of fuel at constant volume. For this reason modern diesel engines operate on dual combustion cycle in which, part of combustion occurs at constant volume also.

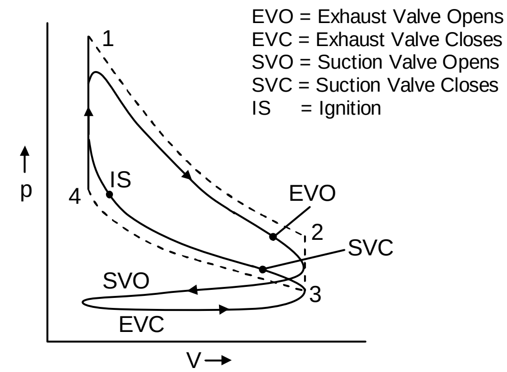

Figure 1.8 : An Indicator Diagram of a Petrol Engine

In actual engine cylinders, the entry and exit of gases takes place through valves which are opened and closed at right moments. Separate mechanisms for valves are provided in the engine. The pressure losses occur at the valves and the ideal cycles lose their sharpness at points where process changes. For example, sharp change at point 2 in Figure 1.4 will not be practically as sharp as shown in this Figure. If we obtain actual pV diagram from an engine, this diagram must be the operation cycle of the engine. For example if pV diagram is obtained from a spark ignition (petrol) engine then this diagram should be an Otto cycle. Further the ideal cycle assumes some air or medium being heated and cooled cycle after cycle but in actual engine fresh charge is taken in and spent gases are exhausted. Therefore, this effect will also appear on the diagram obtained from the engine. The pV diagram sensed from the engine is called its indicator diagram.
Figure 1.8 shows an indicator diagram of a petrol engine and an Otto cycle is superimposed upon it (shown in broken lines).

The suction and exhaust lines can be clearly seen in indicator diagram. The area enclosed between these lines represent the loss of work.

1.10 MEAN EFFECTIVE PRESSURE

Mean effective pressure is the mean height of the pV diagram. It can be calculated theoretically from

$$\text{m.e.p} = \frac{\text{Work done per cycle}}{\text{Stroke volume}} \quad \ldots (1.10)$$

Mean effective pressure is that imaginary pressure which when will act continuously on the piston will perform the same work as the varying pressure will perform. The m.e.p is supposed to perform work only in one stroke which is power stroke. When from an experimental measurement actual indicator diagram of the engine is obtained, the mean effective pressure is calculated from

diagram
agram . . . (1.11)

In a petrol engine the swept volume (stroke volume) is 0.13 m^3. The temperature T_1 = 2000 K, T_2 = 977 K, T_3 = 333 K and T_4 = 681 K. The engine produces power stroke once in 2 revolution. The engine runs at 1000 r.p.m. Calculate

(a) Heat supplied

(b) Heat rejected

(c) Work done (all per cycle and per minute).

If the CV of the fuel is 45000 J/kg, what amount of fuel is required per minute? Use C_v = 713 J/kg K, m = 0.1615 kg.

Solution

Refer Figure 1.8.

Heat is supplied from 4 to 1 which is constant volume process.

$$Q_{41} = m\,C_v\,(T_1 - T_4)$$

$$= 0.1615 \times (2000 - 681) \times 713$$

$$= 152 \times 10^3 \text{ J/cycle}$$

Heat is rejected from 2 to 3 (a constant volume process)

$$Q_{23} = m\,C_v\,(T_2 - T_3)$$

$$= 0.1615 \times 713\,(977 - 333)$$

$$= 74.2 \times 10^3 \text{ J/cycle}$$

∴ Work done by the engine

$$W = Q_{41} - Q_{23} = (152 - 74.2)\,10^3$$

$$= 77.8 \times 10^3 \text{ J/cycle} \qquad \ldots \text{(i)}$$

Since engine requires two revolution to complete a cycle and engine makes 1000 revolution in a minute.

Work done in a minute

$$= \frac{W \times N}{2} = \frac{77.8 \times 10^3 \times 1000}{2}$$

$$= 38.9 \times 10^6 \text{ J/min} \qquad \ldots \text{(ii)}$$

$$\text{Power} = \frac{\text{Work}}{s} = \frac{38.9 \times 10^6}{60} \text{ J/s or W}$$

$$= 648 \text{ kW} \qquad \ldots \text{(iii)}$$

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{W}{Q_{41}}$$

$$\eta = \frac{77.8 \times 10^3}{152} = 0.51 \text{ or } 51\% \qquad \ldots$$

...l by fuel

$$Q_{41} = m_f \times CV$$

$$\text{Mass of fuel } = m_f = \frac{Q_{41}}{CV} = \frac{152 \times 10^3}{45 \times 10^3} \text{ kg per cycle}$$

$$= 3.37 \text{ kg/cycle}$$

$$\text{Mass of fuel per min } = \frac{3.37 \times 1000}{2} = 1685 \text{ kg/min} \qquad \ldots$$

(v)

$$\text{m.e.p} = \frac{\text{Work done}}{\text{Stroke volume}}$$

$$= \frac{77.8 \times 10^3}{0.13}$$

$$= 0.6 \text{ MPa}$$

Example 1.5

If stroke of the engine is two times its diameter of the cylinder in the Example 1.4, can you calculate the work done upon the piston in one cycle?

Solution

Let diameter of the cylinder = d

$$\text{Then area on which m.e.p acts } = \frac{\pi}{4} d^2$$

$$\text{Swept volume (stroke volume) } = \frac{\pi}{4} d^2 \times 2d$$

Since stroke, $l = 2d$

$$\therefore \qquad \frac{\pi}{2} d^3 = 0.13 \text{ m}^3$$

$$\therefore \qquad d = \frac{(2 \times 0.13)^{1/3}}{\pi}$$

$$d = 0.436 \text{ m}$$

$$l = 0.872 \text{ m}$$

The force on the piston, F = m. e. p × area of piston

$$\text{m.e.p} = 0.6 \times 10^6 \text{ N/m}^2 \text{ (from Example 1.1)}$$

$$\therefore \qquad F = 0.6 \times 10^6 \times \frac{\pi}{4} (0.436)^2$$

$$= 0.09 \times 10^6 \text{ N}$$

This force displaces the piston over a distance equal to stroke.

$$W = F \times l$$

$$= 0.09 \times 10^6 \times 0.872$$

e or per cycle.

l as 77.8 × 10^3 J/cycle.

SAQ 1

(a) On how many criteria you can classify an IC Engine?

(b) In Example 1.4 all the heat of fuel has been assumed to have been converted in work. Is it possible? Is there any other way of using the heat of fuel?

(c) A gas engine working on Otto cycle has a cylinder diameter 178 mm and stroke of 254 mm. The clearance volume is 1.5 × 10^6 mm^3. Calculate air standard efficiency.

(d) In an air standard Carnot cycle heat is transferred to the working fluid at 410 K and heat is rejected at 276 K. The heat transfer to working fluid is 110 kJ/kg. The minimum pressure in the cycle is one atm. Assuming constant specific heat of air, determine the cycle efficiency.

Use R = 287 J/kg K.

1.11 SUMMARY

The natural process requirement is that charge should be inhaled, be compressed to the smallest possible volume (clearance volume), fuel should burn and expansion should take place. The charge may consist of a mixture of fuel and air in case of engine operating on Otto cycle and fuel will be such that can evaporate easily and mixed intimately with air. The gaseous fuel and petrol (gasoline) are such fuels. The charge is compressed to the extent, the fuel does not ignite on its own. The compression ratio is limited to 7 or 8. To cause ignition a spark is generated.

The other kind of IC engine is the one which operates on Diesel cycle and uses diesel fuel, another petroleum derivative. The air is the charge which is compressed to a high pressure and temperature (compression ratio of 14 to 22). The temperature of compressed air is greater than auto ignition temperature of diesel fuel which is injected into clearance volume through an injector. The combustion occurs without any external aid.

1.12 ANSWERS TO SAQs

SAQ 1

(a) Fuel type, Ideal cycle of operation, Number of strokes of piston per cycle of operation, Type of ignition, Governing, Number of cylinders.

(b) All the heat produced by the fuel is not converted into work. Part of the heat is carried away by exhaust gases and this has been taken into account by way of ñheat rejectedò. Some heat is also rejected to cooling medium which is ater flowing through jacket of cylinder and head. This heat is about eat of fuel, which means

ne per cycle = Q_{41} ï 0.25 Q_{41} ï Q_{23}

$= (0.75 \times 152$ ï $74.2)\ 10^3$

$= 39.8 \times 10^3$ J

$$\text{Work done per sec.} = \frac{39.8 \times 10^3 \times 1000}{2 \times 60}$$

= 331.7 kJ/s

Power = 331.7 kW

(c) $\text{Stroke Volume} = \frac{\pi}{4} d^2 L = \frac{\pi}{4} (177.56)^2 \times 254 = 6.286 \times 10^6 \text{ mm}^3$

$= v_2 - v_1$

Total cylinder volume

$$= v_2 - v_1 + v_1 = (6.286 + 1.5) \times 10^6 = v_2 = 7.786 \times 10^6 \text{ mm}^3$$

$$\text{Compression ratio} = r = \frac{v_2}{v_1} = \frac{7.786}{1.5} = 5.2$$

Use $\gamma = 1.4$

$$\therefore \quad \eta = 1 - \frac{1}{r^{\gamma - 1}} = 1 - \frac{1}{(5.2)^{0.4}} = 0.475 \text{ or } 47.5\%.$$

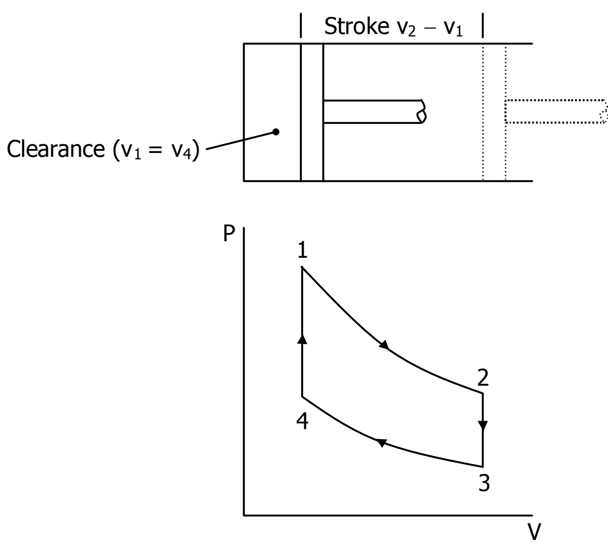

Figure 1.9 : Otto Cycle

(d) $T_1 = 410$ K, $T_3 = 276$ K

$$\eta = \frac{T_1 - T_3}{T_1} = \frac{410 - 276}{410} = 0.327 \quad \text{or} \quad 32.7\%.$$