3 THERMODYNAMICS OF IC ENGINE

In this chapter the laws relating to the behaviour of gas which affect IC engines are briefly discussed.

3.1 GAS LAWS

Some of the important gas laws are given below.

Boyle's Law

If gas in a cylinder is compressed, its volume decreases and a rise in pressure takes place. Also a rise in temperature takes place owing to the heat generated in producing compression. The fall in volume and rise in pressure have a definite relationship as defined by Boyle's law. It states: *If the temperature of a gas is kept constant, the volume of a specific mass (m) of a gas is inversely proportional to the pressure.* Mathematically it may be written as

$$V \propto \frac{1}{P} \qquad (3.1)$$

To express it in another way, for a gas at a specific pressure and temperature

$$V \propto m \qquad (3.2)$$

Combining relations (3.1) and (3.2), we get

$$V \propto \frac{m}{P}$$

If the constant of proportionality is k, we have

$$V = \frac{m}{P} k, \text{ or } PV = mk$$

If V_1 is the volume of a gas at pressure P_1 and V_2 represents the volume of the same gas when pressure is P_2, we have

$$P_1V_1 = P_2V_2 = C \qquad (3.1)$$

where C is a constant.

Charles' Law

Heat is generated when a gas is compressed and it is released when the volume of the gas is increased. We may say that the volume of a gas increases when its temperature is raised and vice versa.

If the pressure of a particular quantity of gas is kept constant, the volume will change 1/273rd part of its volume at 0°C for each degree of temperature change.

Also, if a gas is not allowed to expand (volume remains constant) when its temperature increases, the pressure will increase by 1/273 of its value for each degree rise in temperature above 0°C.

The temperature-pressure-volume relationship of a gas is known as Charles' law and is stated thus: *At constant pressure, the volume of a mass of gas is directly proportional to its absolute temperature.* Mathematically, we have

$$V \propto T$$

It may also be stated thus: *The volume remaining constant, the pressure of a gas is directly proportional to its absolute temperature*, i.e.

$$P \propto T$$

If volume V_1 of a gas changes to volume V_2 when absolute temperature T_1 changes to T_2, pressure remaining constant, we get

$$V_1 T_2 = V_2 T_1$$

Note: When temperature is measured from −273°C as zero, it is known as *absolute temperature* and is the value where molecules of a gas have no motion.

Combination of Boyle's and Charles' Laws

From the above two laws we conclude that in case the pressure of a gas is changing, Charles' law cannot be applied and when temperature changes Boyle's law is not applicable. But in practice, the pressure, volume and temperature of a gas change simultaneously. Therefore, to understand the behaviour of a gas in such cases the two laws have been combined.

By Boyle's law $V \propto \frac{1}{P}$ when T is constant

By Charles' law $V \propto T$ when P is constant

Therefore,

$$V \propto \frac{T}{P} \text{ when } P \text{ and } T \text{ both change}$$

or

$$V = \frac{CT}{P}$$

where C is a constant of proportionality

If $C = MR$ where M is the mass of gas considered and R is the specific gas constant, then

$$PV = MRT$$

For unit mass of gas, since $M = 1$, we get

$$PV = RT \tag{3.4}$$

3.1.1 ISOTHERMAL CHANGE

The change of state of a gas with respect to pressure and volume when temperature remains constant is known as *isothermal change* (Boyle's law). Figure 3.1 shows the behaviour of a gas under such change.

3.1.2 ADIABATIC CHANGE

When a gas is compressed in a cylinder, and the walls of the cylinder and piston are absolute non-conductors of heat, whatever heat is generated due to the compression of the gas will remain in the gas itself. Such compression/expansion of a gas when enclosed in such a non-conducting cylinder is called *adiabatic* (Fig. 3.1). The compression of air in an "air cooled" compressor cylinder is practically adiabatic, as the time is so short that little heat can escape through the walls. According to Boyle's law $PV = C$ (at constant temperature). Therefore, if a gas is subjected to adiabatic compression, the change in temperature also affects the pressure produced and an additional factor must be introduced. Therefore, for adiabatic compression $PV^k = C$. This exponential K varies with the initial pressure and nature of gas. In general practice, the equation of a curve representing the adiabatic change of a gas is

$$P_1 V_1^k = P_2 V_2^k$$

and

$$\frac{T_1}{T_2} = \left[\frac{V_2}{V_1}\right]^{k-1} \tag{3.5}$$

The value of k for air at atmospheric pressure (1.033 kg/cm²) is 1.40.

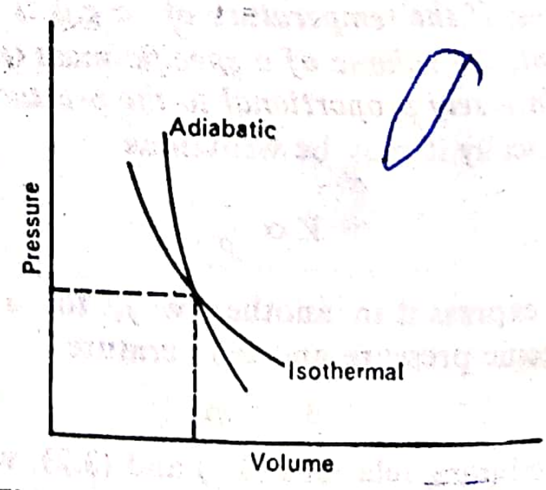

Fig. 3.1 *PV* diagram for adiabatic and isothermal change

3.1.3 THEORETICAL HEAT CYCLES

There are two theoretical cycles of the engine: (i) otto cycle and (ii) diesel cycle. In each of these, a given quantity of pure air is subjected to certain adiabatic compression and expansion.

Ideal Otto Cycles

The diagrammatic representation of such a cycle is given in Fig. 3.2

The sequence of operations in this cycle is as follows :

1. AB represents the admission of air slightly below the atmospheric pressure.
2. BC represents compression under adiabatic condition (without gain or loss of heat from or to the cylinder walls). This operation raises the temperature of the air through a certain range.
3. Ignition occurs at C and the combustion is instantaneous, i.e. rise in pressure CD occurs at a constant volume V_2.
4. DE represents adiabatic expansion during the power stroke. The pressure and temperature of the air falls in this stage.
5. Finally at the lowest pressure (E) the heat remaining in the air is rejected and both pressure and temperature fall to their initial values at the commencement of the cycle.

Analysing the heat and energy reactions of the cycle, we find that heat is added along CD and lost along EB. We can write

$$Q_1 = \text{heat added} = C_V\,(T_D - T_C) \tag{3.6}$$

$$Q_2 = \text{heat lost} = C_V\,(T_E - T_B) \tag{3.7}$$

Theoretical thermal efficiency

$$e = \frac{Q_1 - Q_2}{Q_1} \tag{3.8}$$

Substituting values of Q_1 and Q_2, Eq. (3.8) becomes

$$e = 1 - \frac{T_E - T_B}{T_D - T_C} \tag{3.9}$$

From the gas laws, we have

$$\frac{P_B V_B}{T_B} = \frac{P_C V_C}{T_C} = \frac{P_D V_D}{T_D} = \frac{P_E V_E}{T_E}$$

and

$$P_B V_B^k = P_C V_C^k \text{ and } P_D V_D^k = P_E V_E^k$$

Substituting the values in Eq. (3.9), we get

$$e = 1 - \frac{T_B}{T_C}$$

$$= 1 - \left(\frac{P_B}{P_C}\right)^{(k-1)/k}$$

$$= 1 - \left(\frac{V_C}{V_B}\right)^{k-1} \tag{3.10}$$

It should be mentioned that the cycle described above forms the basis of operation of the four-stroke petrol engine cycle, although the pressure-volume diagram of this engine differs in several respects from the ideal diagram. In the first place, neither the expansion nor the compression processes are fully adiabatic. Again, heat addition and heat rejection processes do not always occur at constant volume. Although by suitably timing the ignition, the

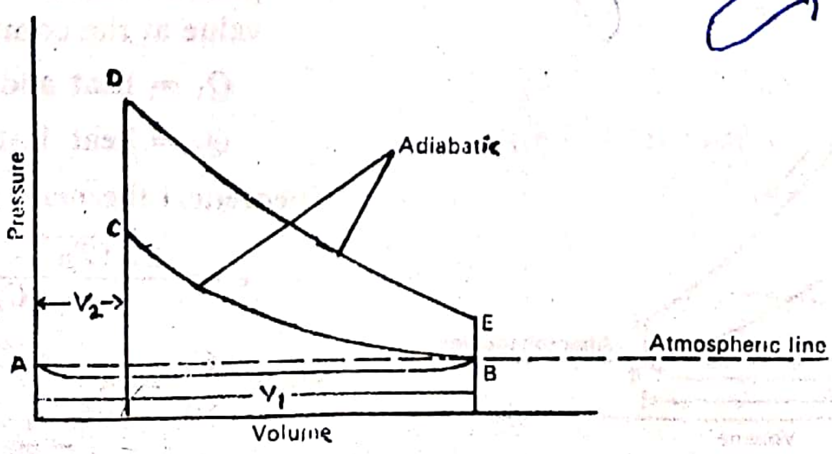

Fig. 3.2 Ideal Otto cycle

pressure rise line can be made practically parallel with the pressure ordinate line.

Also, the specific heat of the petrol-air mixture is not constant as the theory presupposes. It varies with temperature so that the temperature rise due to any given heat addition cannot be estimated in a simple manner.

The actual *PV* diagram of a four-stroke engine is shown in Fig. 3.3.

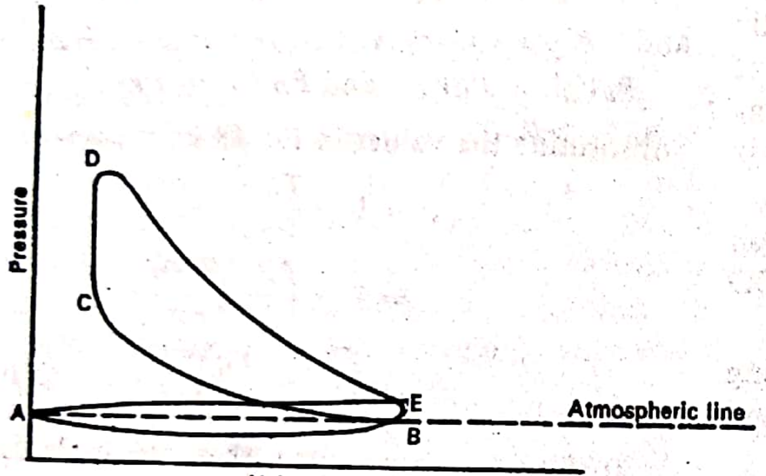

Fig. 3.3 Actual Otto cycle

Constant Pressure Cycle (Diesel Engine)

In this cycle a given quantity of air is assumed to be contained in a cylinder fitted with a freely moving but air-tight piston. Figures 3.4 and 3.5 show ideal and actual diesel cycles respectively.

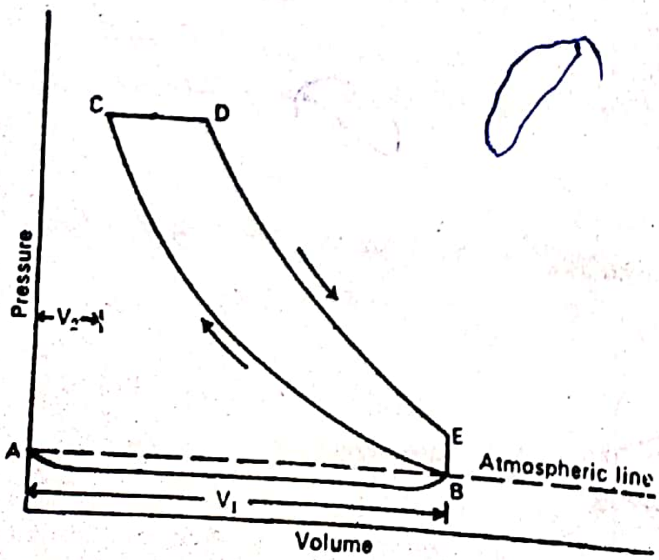

Fig. 3.4 Ideal diesel cycle

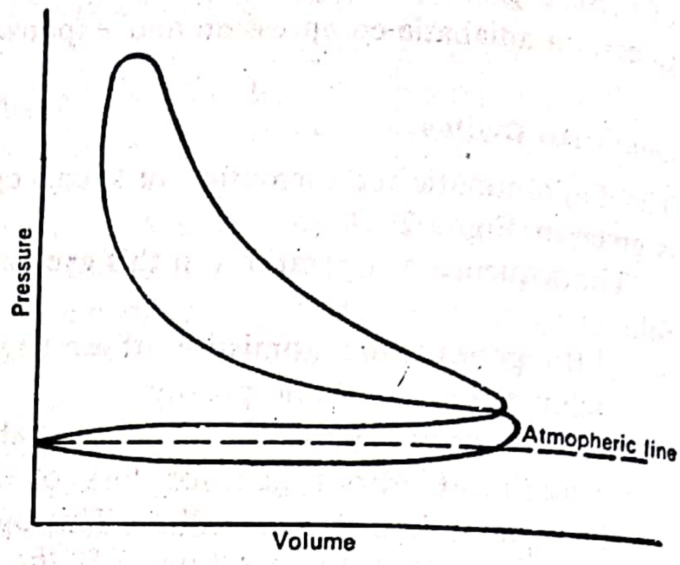

Fig. 3.5 Actual diesel cycle

The sequence of operations is as follows:

1. AB represents admission of air, slightly lower than the atmospheric line.
2. Air is compressed adiabatically (CD) without gain or loss of heat from or to the cylinder walls. This operation raises the temperature of the air through a certain range.
3. Heat supply is then added at the upper constant pressure (CD) and hence at increasing temperature (injection of fuel).
4. Adiabatic expansion then occurs (CD). The pressure and temperature of the air both falling on the piston move it outward.
5. Finally, at the lowest pressure the heat remaining in the air is rejected and both pressure and temperature fall to their initial value at the commencement of the cycle.

Q_1 = heat added = $C_P\,(T_D - T_C)$

Q_2 = heat lost = $C_V\,(T_E - T_B)$

Theoretical thermal efficiency

$$e = \frac{C_P\,(T_D - T_C) - C_V\,(T_E - T_B)}{C_P\,(T_D - T_C)}$$

Since, $\frac{C_P}{C_V} = k$

$$e = 1 - \frac{1}{k}\left[\frac{T_E - T_B}{T_D - T_C}\right] \quad (3.11)$$

From the gas laws, we have

$$\frac{P_B V_B}{T_B} = \frac{P_C V_C}{T_C} = \frac{P_D V_D}{T_D} = \frac{P_E V_E}{T_E}$$

and $P_B V_B^k = P_C V_C^k$ and $P_D V_D^k = P_E V_E^k$

Substituting these value in Eq. (3.11), we get, theoretical efficiency

$$e = 1 - \left(\frac{P_B}{P_C}\right)^{(k-1)/k} \left[\frac{(V_D/V_C)^k - 1}{k[(V_D/V_C) - 1]}\right] \quad (3.12)$$

Constant volume - otto cycle - Petrol engine - four stroke

constant pressure - Diesel engine -

OBJECTIVE QUESTIONS

1. When ----- of a gas is changing charle's law cannot be applied.
2. Boyle's law cannot be applied when ----- of a gas is changing.
3. In ----- expansion or compression, the gas neither receives nor rejects the heat.
4. The efficiency of diesel cycle is influenced not only by the ----- but also by the length of time during which the heat is added to the compressed air.
5. ----- is also called as constant volume process.
6. ----- is also called as constant pressure process.
7. Efficiency of dieseal cycle increases as the compression ratio ------- & fuel cut off ratio--------
8. In air std. otto cycle, heat addition takes place at const ------
9. In air std. diesel cycle, heat addition takes place at const ------
10. In air std. otto cycle the compression and expansion are ----------- processes
11. In air std. diesel cycle the compression and expansion are ----------- processes

ANSWERS

1. Pressure
2. Temperature
3. Adiabatic
4. Compression ratio
5. Otto
6. Diesel
7. Increases,....dercreases
8. Volume
9. Pressure
10. Adiabatic
11. Adiabatic