

## ENGINE

An engine is a device which transforms one form of energy into another form.

## HEAT ENGINE

Heat engine is a device which transforms the chemical energy of a fuel into thermal energy and utilizes this thermal energy to perform useful work. Thus, thermal energy is converted to mechanical energy in a heat engine.

Generally source of heat is combustion chamber or furnace where combustion of fuel takes place. Heat is continuously supplied to the medium from the combustion chamber for conversion into mechanical work.

In addition to the above three elements, there is one cold body, at a lower temperature than the source is known as *heat sink*.

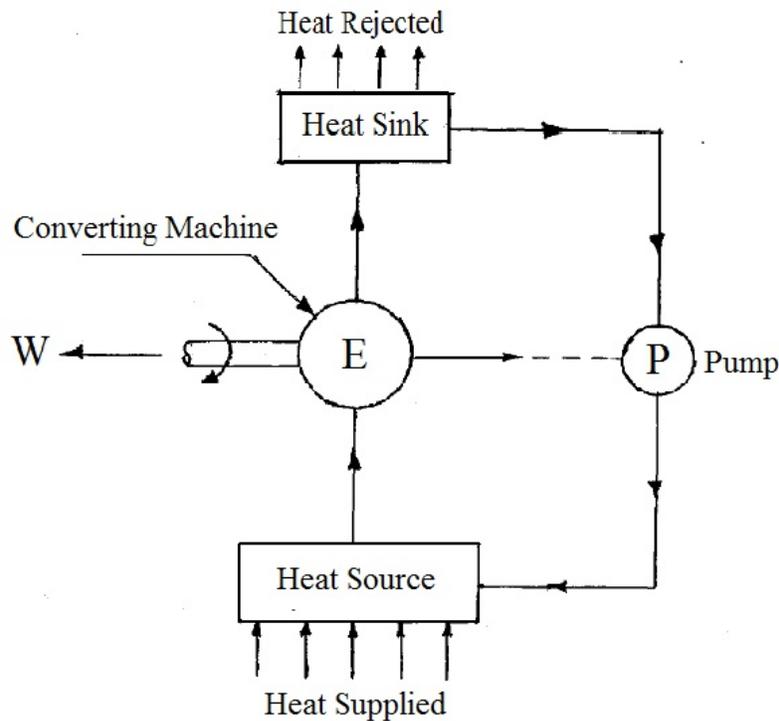


Fig. 5.1 Elementary Heat Engine

Fig. 5.1 illustrates the basic principle of an elementary heat engine. The working fluid takes heat from heat source and flows to the converting machine E where heat energy converts into mechanical work.

After this conversion it is discharged into the sink where it is cooled and comes to the original state. From the heat sink working fluid is supplied to heat source by the pump P, where it is heated again and cycle is repeated.

## Classification of Heat Engine:

Heat engine are divided into two broad classes:

- 1) External combustion engine

### 2) Internal combustion engine

#### 1) *External Combustion Engine:*

In this case, combustion of fuel takes place outside the cylinder as in case of steam engines where the heat of combustion is employed to generate steam which is used to move a piston in a cylinder. Other examples of external combustion engine are hot air engines, steam turbine and closed cycle gas turbine. These engines are generally used to drive locomotives, ships, generation of electric power etc.

#### 2) *Internal Combustion (IC) Engine:*

In this case combustion of fuel with oxygen of the air occurs within the cylinder of the engine. The internal combustion engines group includes engines employing mixture of combustible gases and air, known as gas engines, those using lighter liquid fuel or spirit known as petrol engines and those using heavier liquid fuels, known as oil compression ignition or diesel engines.

## Advantages of Heat Engines:

The advantages of internal combustion engines are:

- 1) Greater mechanical efficiency.
- 2) Lower weight and bulk to output ratio.
- 3) Lower first cost.
- 4) Higher overall efficiency.
- 5) Lesser requirement of water for dissipation of energy through cooling system.
- 6) The advantage of external combustion engines are:
- 7) Use of cheaper fuels.
- 8) High starting torque.
- 9) Higher weight and bulk to output ratio.

## DEFINITIONS

### Working substance

When a gas or mixture of gases or a vapour is used in engine for transferring heat, it is known as working fluid or working substance.

Working fluids are able to absorb heat, store within them and give up heat when required. During the process of absorbing and giving up heat, its pressure, volume, and temperature changes accordingly. Working fluid is never destroyed or reduced in quantity during the process.

### Converting machines

Any machine, which converts heat energy of the working fluid into mechanical work is called converting machine.

### Reciprocating machine

It is the machine consisting of a hollow cylinder into which a piston reciprocates by the action of a working fluid.

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### Rotary machine

It is the machine consisting of a wheel, fixed on a shaft, fitted with blades or vanes rotating due to the action of the working fluid upon the blades.

### Jet machine

It is the machine in which the fluid is discharged from the machine in the form of a jet and producing an impact which causes the motion.

### Cycle

It is defined as a series of processes performed in a definite order or sequence so that, after different and definite number of processes, all the concerned substances are returned to their original state and condition.

### Direct cycle

A heat engine, operating on a cycle produces or develops Mechanical energy or work is said to be working on a direct cycle.

### Reversed cycle

If the sequence of operation or processes in direct cycle are reversed it is said to be operating on reversed cycle.

## Heat engine cycles

Following are the various heat engine cycles which will be discussed in detail in this chapter.

(1) Carnot cycle      (2) Rankine cycle      (3) Otto cycle      (4) Diesel cycle

### Carnot Cycle

Sadi Carnot in 1824 first proposed the concept of heat engine working on reversible cycle called Carnot cycle.

According to **Carnot theorem** "No cycle can be more efficient than a reversible cycle operating between the same temperature limits."

Carnot cycle is useful to compare the efficiency of any cycle under consideration with the efficiency of any cycle operating between the same two temperatures.

A Carnot cycle is a hypothetical cycle consisting four different processes: two reversible isothermal processes and two reversible adiabatic (isentropic) processes.

#### Assumptions made in the working of the Carnot cycle

- a) Working fluid is a perfect gas.
- b) Piston cylinder arrangement is weightless and does not produce friction during motion.
- c) The walls of cylinder and piston are considered as perfectly insulated.
- d) Compression and expansion are reversible.
- e) The transfer of heat does not change the temperature of sources or sink.

Fig. 5.2 shows essential elements for a Carnot cycle, P-v and T-S diagrams.

This cycle has the highest possible efficiency and it consists four simple operations as below:

1. Isothermal Expansion (1 – 2)
2. Isentropic Expansion (2 – 3)
3. Isothermal Compression (3 – 4)
4. Isentropic Compression (4 – 1)

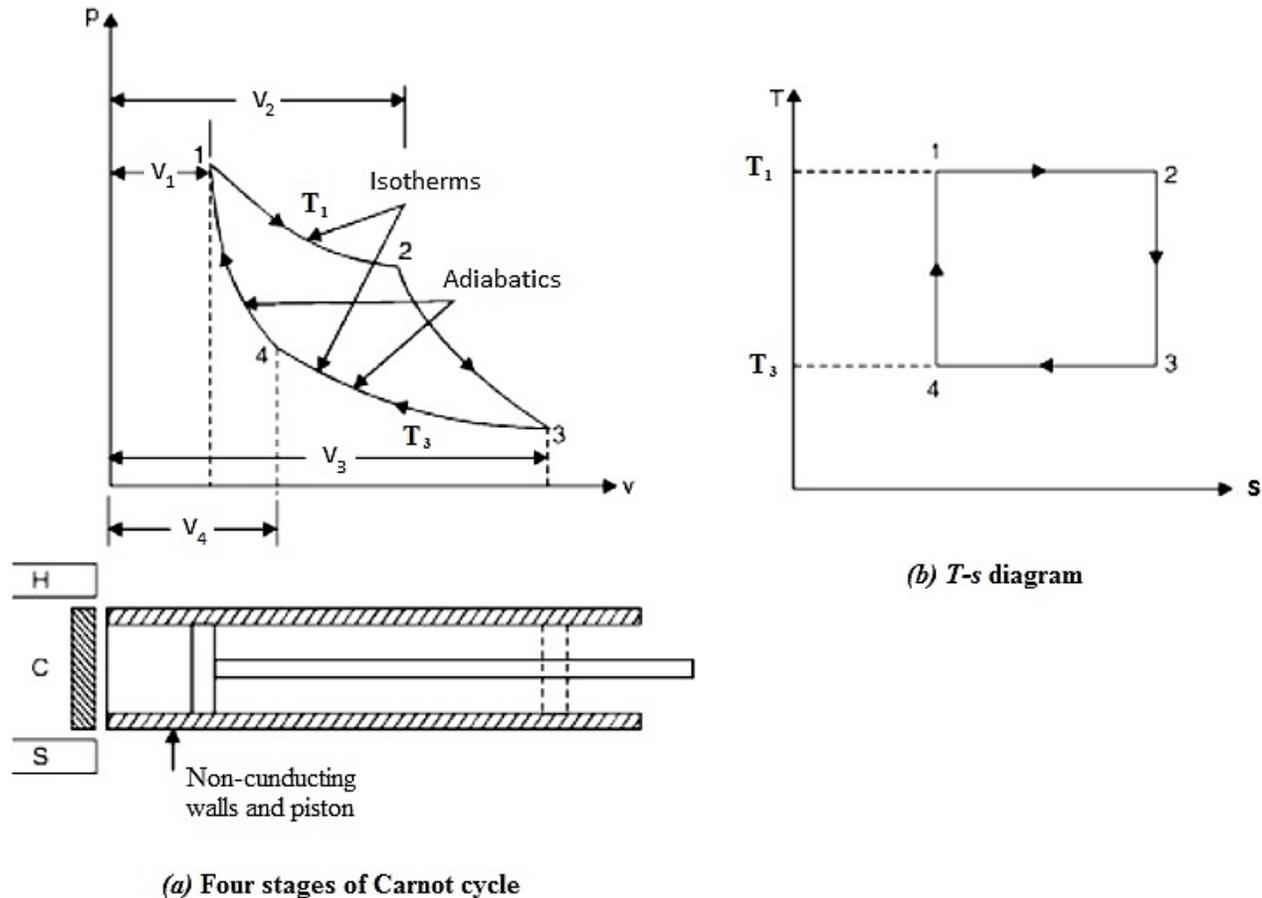


Fig. 5.2 P-v, T-S and schematic diagram of Carnot gas power cycle

**Isothermal expansion (1 – 2):-**

The source of heat (H) is applied to the end of the cylinder and isothermal reversible expansion occurs at temperature  $T_1$ . During this process  $Q_1$  heat is supplied to the system.

**Adiabatic expansion (2 – 3):-**

Adiabatic cover (C) is brought in contact with the cylinder head. The cylinder becomes perfect insulator because of non-conducting walls and end. Hence no heat transfer takes place. The fluid expands adiabatically and reversibly. The temperature falls from  $T_1$  to  $T_3$ .

**Isothermal compression (3 – 4):-**

Adiabatic cover is removed and sink (S) is applied to the end of the cylinder. The heat,  $Q_2$  is transferred reversibly and isothermally at temperature  $T_3$  from the system to the sink (S).

**Adiabatic compression (4 – 1):-**

Adiabatic cover is brought in contact with cylinder head. This completes the cycle and system is returned to its original state at 1. During the process, the temperature of system is raised from  $T_3$  to  $T_1$ .

**Efficiency of Carnot cycle:**

Consider 1 kg of working substance

Heat supplied during isothermal process (1-2)

$$Q_1 = p_1 V_1 \ln \frac{V_2}{V_1}$$

$$\therefore Q_1 = RT_1 \ln \frac{V_2}{V_1} \quad (5.1)$$

Heat rejected during isothermal compression (3-4);

$$Q_2 = p_3 V_3 \ln \frac{V_4}{V_3}$$

$$Q_2 = RT_3 \ln \frac{V_4}{V_3} \quad (5.2)$$

During **adiabatic expansion (2-3)** and **adiabatic compression (4-1)**, the heat transfer from or to the system is **zero**.

Work done,

$$W = Q_1 - Q_2$$

$$\therefore W = RT_1 \ln \frac{V_2}{V_1} - RT_3 \ln \frac{V_4}{V_3} \quad (5.3)$$

Let,  $r$  = ratio of expansion for process (1 – 2) =  $\frac{V_2}{V_1}$

= ratio of compression for process (3 – 4) =  $\frac{V_4}{V_3}$

by substituting the value of  $r$  in equation 5.3, we get,

$$W = RT_1 \ln r - RT_3 \ln r$$

$$\therefore W = R \ln r (T_1 - T_3) \quad (5.4)$$

**Thermal efficiency,**

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{Q_1 - Q_2}{Q_1}$$

$$\therefore \eta = \frac{R \ln r (T_1 - T_3)}{RT_1 \ln r}$$

$$\therefore \eta = \frac{T_1 - T_3}{T_1} = 1 - \frac{T_3}{T_1} \quad (5.5)$$

Where,

$T_1$  = Maximum temperature of the cycle (K)

$T_3$  = Minimum temperature of cycle (K)

In equation 5.5, if temperature  $T_3$  decreases, efficiency increases and it becomes 100% if temperature  $T_3$  becomes absolute zero; which is **impossible** to attain.

#### Limitations of Carnot Gas Cycle:

- The Carnot cycle is hypothetical.
- The thermal efficiency of Carnot cycle depends upon absolute temperature of heat source  $T_1$  and heat sink  $T_3$  only, and independent of the working substance.
- Practically it is not possible to neglect friction between piston and cylinder. It can be minimized but cannot be eliminated.
- It is impossible to construct cylinder walls which are perfect insulator. Some amount of heat will always be transferred. Hence perfect adiabatic process cannot be achieved.
- The isothermal and adiabatic processes take place during the same stroke. Therefore the piston has to move very slowly for isothermal process and it has to move very fast during remaining stroke for adiabatic process which is practically not possible.
- The output obtained per cycle is very small. This work may not be able to overcome the friction of the reciprocating parts.

## Rankine Cycle

The Rankine cycle is the ideal cycle for steam power plants. In a steam power plants, the heat energy of the fuel is converted into mechanical energy or power.

The ideal Rankine cycle is shown schematically and on P-V, T-s & h-s diagram in Fig. 5.3. The liquid, vapour and wet regions are also indicated with the help of saturation curve.

#### **Process 4 – 1: Constant pressure heat addition in the boiler**

The water is heated at constant pressure  $p_1$  in the boiler until the saturation temperature is reached, Saturated water is converted into saturated steam at constant pressure. During 1-1' process steam is superheated in super heater.

Heat supplied is given by

$$Q_s = h_1 - h_4$$

#### **Process 1 – 2: Isentropic expansion in the turbine**

## 5. Heat Engine

High pressure and high temperature superheated, dry saturated or wet steam generated in the boiler at  $p_1$  and  $T_1$  is supplied to the steam turbine. This steam expands isentropically into steam turbine up to the condenser pressure. Steam turbine develops mechanical work,  $W_T$  due to expansion of steam.

Turbine work is given by,

$$W_T = h_1 - h_2$$

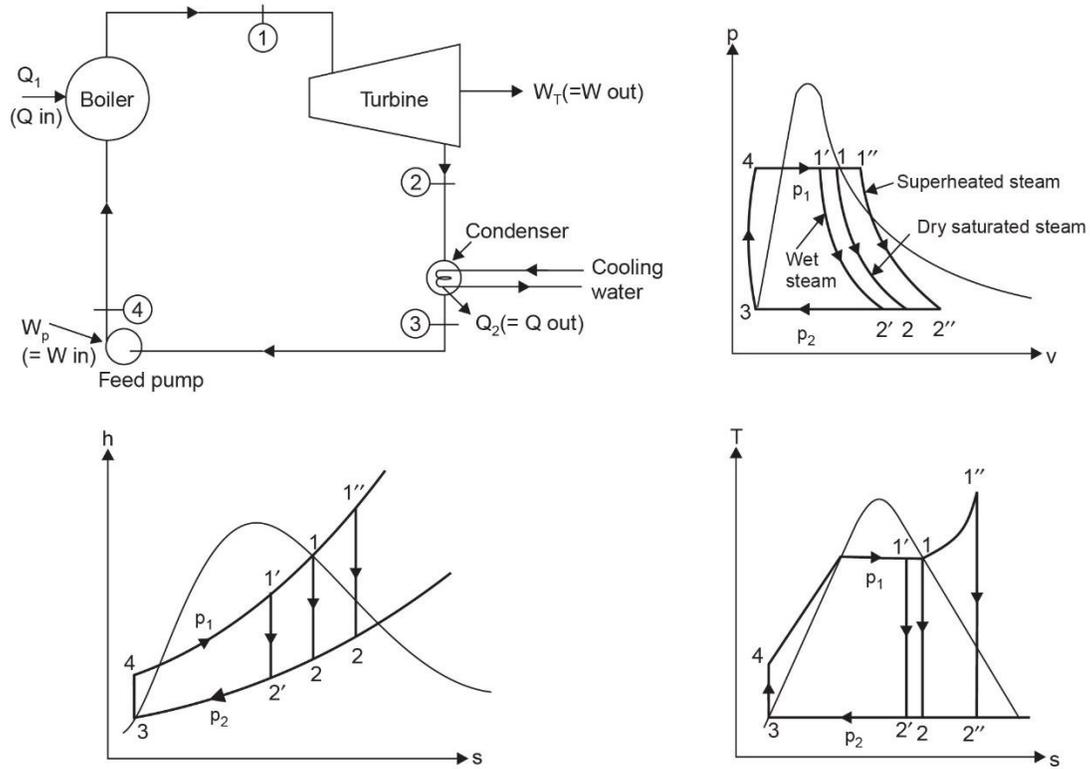


Fig. 5.3 p-V, T-s, h-s and schematic diagram of Rankine cycle

### Process 2 – 3: Constant pressure heat rejection in the condenser

The exhaust steam from turbine enters into condenser, where it is condensed at constant pressure by circulating cooling water in the tubes. The heat rejected by exhaust steam is  $Q_R$ .

Heat rejected is given by,

$$Q_R = h_2 - h_3$$

### Process 3 – 4: Isentropic compression in the pump (Pumping Process)

The condensed water coming from condenser is pumped to boiler at boiler pressure with the help of feed pump. To do so work,  $W_P$  is supplied to feed pump.

Pump work is given by,

$$W_P = h_4 - h_3$$

## Efficiency of Rankine Cycle

Thermal efficiency is given by,

$$\text{Efficiency} = \eta_R = \frac{\text{Net work output}}{\text{Heat supplied in boiler}}$$

$$\therefore \eta_R = \frac{W_{net}}{Q_s} \quad (5.6)$$

**Heat supplied** to the working fluid in a boiler during process 4 – 1,

$$Q_s = h_1 - h_4 \quad (5.7)$$

**Turbine work** during process 1 – 2,

$$W_T = h_1 - h_2 \quad (5.8)$$

**Heat rejected** during condensation process 2 – 3,

$$Q_R = h_2 - h_3 \quad (5.9)$$

**Pump work** during process 3 – 4,

$$W_P = h_4 - h_3 \quad (5.10)$$

**Net work output**

$$W_{net} = W_T - W_P$$

$$W_{net} = (h_1 - h_2) - (h_4 - h_3) \quad (5.11)$$

$$\therefore \eta_R = \frac{(h_1 - h_2) - (h_4 - h_3)}{(h_1 - h_4)}$$

$$\therefore \eta_R = \frac{(h_1 - h_4) - (h_2 - h_3)}{(h_1 - h_4)}$$

$$\therefore \eta_R = 1 - \frac{h_2 - h_3}{h_1 - h_4} \quad (5.12)$$

Usually pump work is very small, hence it is neglected

$$\therefore \eta_R = \frac{h_1 - h_2}{h_1 - h_4} \quad (5.13)$$

## Air Standard Cycles

In most of the power developing systems, such as petrol engine, diesel engine and gas turbine, the common working fluid used is air. These devices take in either a mixture of fuel and air as in petrol engine or air and fuel separately and mix them in the combustion chamber as in diesel engine

The mass of fuel used compared with the mass of air is rather small. Therefore the properties of mixture can be approximated to the properties of air.

Exact condition existing within the actual engine cylinder are very difficult to determine, but by making certain simplifying assumptions, it is possible to approximate these conditions more or less closely. The approximate engine cycles thus analysed are known as theoretical cycles.

The simplest theoretical cycle is called the air-cycle approximation. The air-cycle approximation used for calculating conditions in internal combustion engine is called the air-standard cycle.

### Air standard efficiency:

The efficiency of engine in which air is used as working substance is known as *air standard efficiency*.

The air standard efficiency is always greater than the actual efficiency of cycle.

### Assumptions made for analysis of Air standard cycle:

- 1) The working fluid is air.
- 2) In the cycle, all the processes are reversible.
- 3) The air behaves as an ideal gas and its specific heat is constant at all temperatures.  
 $C_p = 1.005 \text{ kJ/kg K}$ ,  $C_v = 0.718 \text{ kJ/kg K}$ ,  $\gamma = 1.4$
- 4) Mass of working fluid remains constant through entire cycle.
- 5) Heat is supplied from constant high temperature heat reservoir. Some heat is rejected from fluid to a heat sink.

## Otto Cycle

Nicholas-A-Otto, a German engineer developed the first successful engine working on this cycle in 1876. This cycle is also known as Constant volume cycle because heat is supplied and rejected at constant volume. Mainly this cycle is used in petrol and gas engines.

Fig. 5.4 shows the Otto cycle plotted on  $p - V$  diagram.

### Adiabatic Compression Process (1 – 2):

At pt. 1 cylinder is full of air with volume  $V_1$ , pressure  $P_1$  and temp.  $T_1$ .

Piston moves from BDC to TDC and an ideal gas (air) is compressed isentropically to state point 2 through compression ratio,

$$r = \frac{V_1}{V_2}$$

### Constant Volume Heat Addition Process (2 – 3):

Heat is added at constant volume from an external heat source.

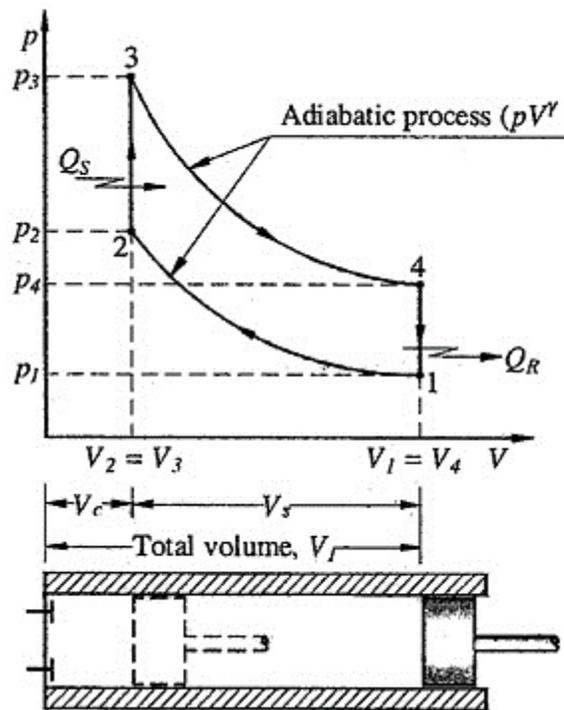


Fig. 5.4 P-V diagram for petrol cycle.

The pressure rises and the ratio  $r_p$  or  $\alpha = \frac{P_3}{P_2}$  is called expansion ratio or pressure ratio.

#### **Adiabatic Expansion Process (3 – 4):**

The increased high pressure exerts a greater amount of force on the piston and pushes it towards the BDC.

Expansion of working fluid takes place isentropically and work done by the system.

The volume ratio  $\frac{V_4}{V_3}$  is called isentropic expansion ratio.

#### **Constant Volume Heat Rejection Process (4 – 1):**

Heat is rejected to the external sink at constant volume. This process is so controlled that ultimately the working fluid comes to its initial state 1 and the cycle is repeated.

Many petrol and gas engines work on a cycle which is a slight modification of the Otto cycle.

This cycle is called *constant volume cycle* because the heat is supplied to air at constant volume.

### **Air Standard Efficiency of an Otto Cycle:**

Consider a unit mass of air undergoing a cyclic change.

Heat supplied during the process 2 – 3,

$$q_1 = C_v (T_3 - T_2)$$

Heat rejected during process 4 – 1,

$$q_2 = C_v (T_4 - T_1)$$

Work done,

$$\therefore W = q_1 - q_2$$

$$\therefore W = C_v (T_3 - T_2) - C_v (T_4 - T_1)$$

Thermal efficiency,

$$\begin{aligned} \eta &= \frac{\text{Work done}}{\text{Heat supplied}} = \frac{W}{q_1} \\ &= \frac{C_v (T_3 - T_2) - C_v (T_4 - T_1)}{C_v (T_3 - T_2)} \\ &= 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} \end{aligned} \quad (5.14)$$

For Adiabatic compression process (1 – 2),

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

$$\therefore T_2 = T_1 r^{\gamma-1} \quad (5.15)$$

For Isentropic expansion process (3 – 4),

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

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

$$\therefore T_3 = T_4 \left( \frac{V_1}{V_2} \right)^{\gamma-1} \quad (\because V_1 = V_4, V_2 = V_3)$$

$$\therefore T_3 = T_4 (r)^{\gamma-1} \quad (5.16)$$

From equation 5.14, 5.15 & 5.16, we get,

$$\eta_{otto} = 1 - \frac{(T_4 - T_1)}{T_4 r^{\gamma-1} - T_1 r^{\gamma-1}}$$

$$\therefore \eta_{otto} = 1 - \frac{(T_4 - T_1)}{r^{\gamma-1} (T_4 - T_1)}$$

$$\therefore \eta_{otto} = 1 - \frac{1}{r^{\gamma-1}} \quad (5.17)$$

Expression 5.17 is known as the air standard efficiency of the Otto cycle.

It is clear from the above expression that efficiency increases with the increase in the value of  $r$  (as  $\gamma$  is constant).

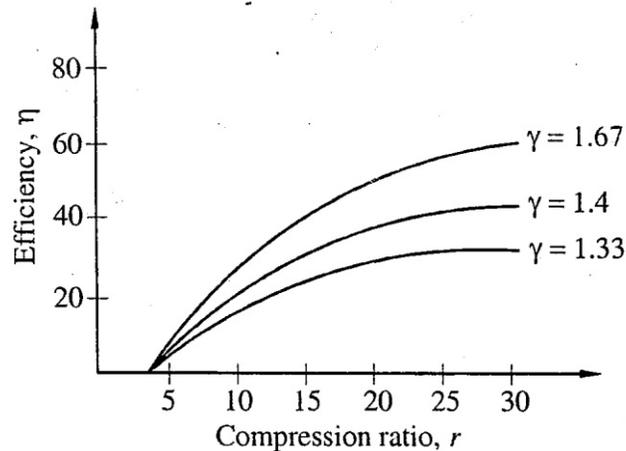


Fig. 5.5 Effect of compression ratio on  $\eta$

Fig. 5.5 shows the variation of air standard efficiency of Otto cycle with compression ratio.

## Diesel Cycle

This cycle was discovered by a German engineer Dr. Rudolph Diesel. Diesel cycle is also known as **constant pressure heat addition cycle**.

The diesel cycle consists of two reversible adiabatic process, a constant pressure process and constant volume process. (p-V) diagram of this cycle is shown in Fig. 5.6.

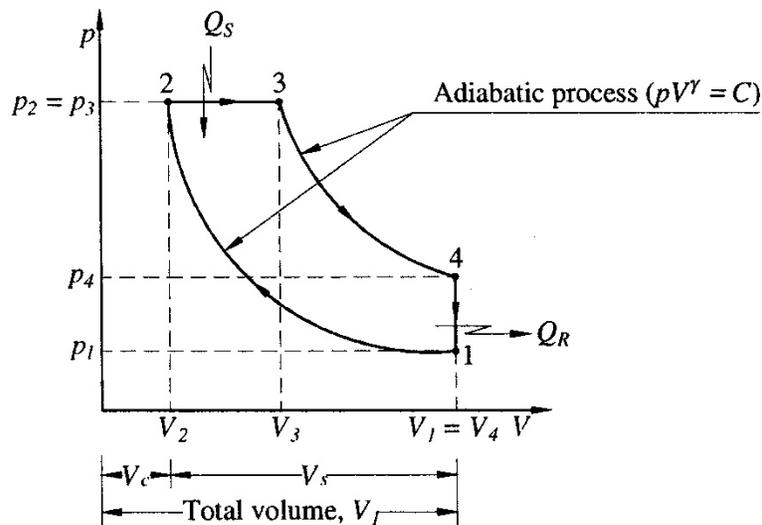


Fig. 5.6 p-V diagram for diesel cycle

### Reversible adiabatic Compression Process (1 – 2):

Isentropic (Reversible adiabatic) compression with  $r = \frac{V_1}{V_2}$ .

### Constant Pressure Heat Addition Process (2 – 3):

During this process heat is added to air at constant pressure. Due to heat addition volume and temperature of air increases. Volume ratio  $\frac{V_3}{V_2}$  is known as cut-off ratio.

$$\therefore \text{Heat supplied, } Q_S = mC_p(T_3 - T_2)$$

### Reversible adiabatic Expansion Process (3 – 4):

Isentropic expansion of air  $\frac{V_4}{V_3}$  = isentropic expansion ratio.

Work is developed during this process.

### Constant Volume Heat Rejection Process (4 – 1):

In this process heat is rejected at constant volume. Hence pressure and temperature of air decreases to initial value. This way cycle is complete.

This thermodynamics cycle is called constant pressure cycle because heat is supplied to the air at constant pressure.

$$\therefore \text{Heat rejected, } Q_R = mC_v(T_4 - T_1)$$

**Fig. 9 p-V diagram for diesel cycle**

### **Efficiency of Diesel cycle:**

$$\begin{aligned} \text{Net work done, } W_{net} &= \text{Heat supplied} - \text{Heat rejected} \\ &= mC_p(T_3 - T_2) - mC_v(T_4 - T_1) \end{aligned}$$

$$\begin{aligned} \text{Air standard efficiency, } \eta &= \frac{\text{Net work done}}{\text{Heat supplied}} \\ &= \frac{mC_p(T_3 - T_2) - mC_v(T_4 - T_1)}{mC_p(T_3 - T_2)} \\ &= 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)} \end{aligned} \tag{5.18}$$

Let,

$$\text{compression ratio, } r = \frac{V_1}{V_2}$$

$$\text{Cut-off ratio, } \rho = \frac{V_3}{V_2}$$

$$\text{Expansion Ratio} = \frac{V_4}{V_3}$$

**For process (1-2):**

$$\begin{aligned} \frac{T_2}{T_1} &= \left( \frac{V_1}{V_2} \right)^{\gamma-1} = r^{\gamma-1} \\ \therefore T_2 &= T_1 \cdot r^{\gamma-1} \end{aligned} \quad (5.19)$$

**For process (2-3)**

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

Since  $p_2 = p_3$  (from fig. 6)

$$\therefore T_3 = T_2 \cdot \frac{V_3}{V_2}$$

By substituting the value of  $T_2$  from eq. (5.19)

$$\therefore T_3 = [T_1 \cdot r^{\gamma-1}] \cdot \rho \quad (5.20)$$

**For process (3-4):**

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

$$\frac{V_4}{V_3} = \frac{V_4/V_2}{V_3/V_2} = \frac{r}{\rho} \quad (\because V_1 = V_4)$$

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

$$\therefore T_4 = T_3 \cdot \frac{\rho^{\gamma-1}}{r^{\gamma-1}}$$

By substituting the value of  $T_3$  from eq. (5.20), we get

$$T_4 = (T_1 r^{\gamma-1} \cdot \rho) \left( \frac{\rho^{\gamma-1}}{r^{\gamma-1}} \right)$$

$$\therefore T_4 = \rho^\gamma \cdot T_1 \quad (5.21)$$

By substituting the values of  $T_2$ ,  $T_3$  and  $T_4$  in eq. (5.18) we get,

$$\begin{aligned}\therefore \eta &= 1 - \frac{1}{\gamma} \left[ \frac{T_1 \cdot \rho^\gamma - T_1}{T_1 \cdot \rho \cdot r^{\gamma-1} - T_1 \cdot r^{\gamma-1}} \right] \\ \therefore \eta &= 1 - \frac{1}{r^{\gamma-1}} \left[ \frac{\rho^\gamma - 1}{\gamma(\rho - 1)} \right] \quad (5.22)\end{aligned}$$

It is clear from the above equation that the efficiency of diesel cycle depends upon compression ratio ( $r$ ), ratio of specific heat ( $\gamma$ ), and cut-off ratio  $\rho$ .

Cut-off ratio  $\rho$  is always greater than 1 and  $\gamma = 1.4$  for air, the quantity in bracket is always greater than one.

The efficiency of Diesel cycle is always less than Otto cycle for same compression ratio due to above reason.

Heat is added at constant volume in Otto cycle while heat is added at constant pressure in Diesel cycle.

From the eq. (5.22) it is clear that the efficiency of Diesel cycle increases with the increase of compression ratio and with the decreases of cut-off ratio.