BRANCH: MECHANICAL ENGINEERING

SEMESTER: 4TH

SUBJECT: THERMAL ENGINEERING - II

FACULTY: Er. SANJAY KUMAR PANIGRAHY

SYLLABUS

1. Performance of I.C engine
1.1 Define mechanical efficiency, Indicated thermal efficiency,
Relative Efficiency, brake thermal efficiency overall efficiency
Mean effective pressure &specific fuel consumption.
1.2 Define air-fuel ratio & calorific value of fuel.
1.3 Work out problems to determine efficiencies & specific fuel consumption.

2. Air Compressor
2.1 Explain functions of compressor & industrial use of compressor air
2.2 Classify air compressor & principle of operation.
2.3 Describe the parts and working principle of reciprocating Air compressor.
2.4 Explain the terminology of reciprocating compressor such as bore, stroke, pressure ratio free air delivered &Volumetric efficiency.
2.5 Derive the work done of single stage & two stage compressor with and without clearance.
2.6 Solve simple problems (without clearance only)

3. Properties of Steam
3.1 Difference between gas & vapours.
3.2 Formation of steam.
3.3 Representation on P-V, T-S, H-S, & T-H diagram.
3.4 Definition & Properties of Steam.
3.5 Use of steam table & mollier chart for finding unknown properties.
3.6 Non flow & flow process of vapour.
3.7 P-V, T-S & H-S, diagram.
3.8 Determine the changes in properties & solve simple numerical.

4. Steam Generator
4.1 Classification & types of Boiler.
4.2 Important terms for Boiler.
4.3 Comparison between fire tube & Water tube Boiler.
4.4 Description & working of common boilers (Cochran, Lancashire, Babcock & Wilcox Boiler)
4.5 Boiler Draught (Forced, induced & balanced)
4.6 Boiler mountings & accessories.

5. Steam Power Cycles
5.1 Carnot cycle with vapour.
5.2 Derive work & efficiency of the cycle.
5.3 Rankine cycle.
5.3.1 Representation in P-V, T-S & h-s diagram.
5.3.2 Derive Work & Efficiency.
5.3.3 Effect of Various end conditions in Rankine cycle.
5.3.4 Reheat cycle & regenerative Cycle.
5.4 Solve simple numerical on Carnot vapour Cycle & Rankine Cycle.

6. Heat Transfer
6.1 Modes of Heat Transfer (Conduction, Convection, Radiation).
6.2 Fourier law of heat conduction and thermal conductivity (k).
6.3 Newton's laws of cooling.
6.4 Radiation heat transfer (Stefan, Boltzmann & Kirchhoff's law) only statement, no derivation & no numerical problem.
6.5 Black body Radiation, Definition of Emissivity, absorptivity, & transmissibility.

1^{ST} CHAPTER
Performance of I.C engine

IC ENGINE:

IC engine is a heat engine where the combustion of the air-fuel mixture occurs inside the combustion chamber that produces high temperature and high gas pressure. This gas pressure pushes the piston over a distance and transforms the chemical energy into thermal energy which is used for performing the mechanical work.

ENGINE PERFORMANCE PARAMETERS:

The engine performance is indicated by the term efficiency, η. Five important engine efficiencies and other related engine performance parameters are:

(1) Indicated thermal efficiency

(2) Brake thermal efficiency

(3) Mechanical efficiency

(4) Volumetric efficiency

(5) Relative efficiency or Efficiency ratio

(6) Mean effective pressure

(7) Mean piston speed

(8) Specific power output

(9) Specific fuel consumption

(10) Fuel-air or air-fuel ratio

(11) Calorific value of the fuel

(1) Indicated Thermal Efficiency (η_{ith}) :

Indicated thermal efficiency is the kind of engine thermal efficiency that is given by the ratio of indicated power generated by the engine to the power generated by the combustion of the fuel.

It states the amount of power taken by the piston out of the total fuel power. The indicated thermal efficiency is denoted by the symbol η_{ith}.

The indicated thermal efficiency is given by,

$$\eta_{\text{indicated}} = \frac{\text{Indicated power}}{\text{Fuel power}}$$

As the fuel power is given by the product of the fuel mass flow rate and calorific value of the fuel.

$$\eta_{\text{indicated}} = \frac{\text{Indicated power}}{\dot{m}_f \times Cv}$$

Indicated power:-

The amount of power developed in the cylinder is known as the indicated power. The indicated power is given by the following equation,

$$I.P = \frac{100\ k\ p_m\ L\ A\ n}{60}\ KW$$

Where,

K = Number of cylinders

Pm = Mean effective pressure

L = Stroke length

A = Cylinder bore cross-section area

n = Number of power strokes per minute

Fuel power:-

Fuel power is the product of the calorific value of the fuel and the mass flow rate of the fuel. The formula of the fuel power is given by,

$$\text{Fuel Power} = \dot{m}_f \times C_V$$

Where,

m_f = Mass flow rate of the fuel

C_V = Calorific value of the fuel

(2) **Brake Thermal Efficiency(η_{bth}):**

Brake thermal efficiency is the ratio of energy in the brake power to the input fuel energy in appropriate units.

The brake thermal efficiency for the engine is given by,

$$\eta_{\text{Brake}} = \frac{\text{Brake power}}{\text{Fuel power}}$$

Where the fuel power is the product of the fuel mass flow rate and the calorific value.

Hence,

$$\eta_{\text{Brake}} = \frac{\text{Brake power}}{\dot{m}_f \times Cv}$$

Brake power:-

Brake power is the amount of power available at the crankshaft of the engine. It is also given by the product of the torque available at the crankshaft and the angular speed of the crankshaft.

Mathematically it is given by,

$$B.P. = T_{\text{Crankshaft}} \times \omega_{\text{Crankshaft}}$$

B.P. = $2\times\pi\times N\times T_{Crankshaft}/60$

Where,

N = RPM of the crankshaft

$T_{Crankshaft} = F_{Crankpin}\times r_{Crank}$

(3) Mechanical Efficiency (η_m):

Mechanical efficiency is defined as the ratio of brake power (delivered power) to the indicated power (power provided to the piston) or can be defined as the ratio of the brake thermal efficiency to the indicated thermal efficiency.

η_m = brake power / indicated power

(4) Relative efficiency(η_{rel}):

It is also known as efficiency ratio. The relative efficiency of an I. C. engine is the ratio of the indicated thermal efficiency to the air standard efficiency.

(5) Overall efficiency(η_o):

It is the ratio of the work obtained at the crankshaft in a given time to the energy supplied by the fuel during the same time.

(6) Mean effective pressure:

Mean effective pressure is the average pressure inside the cylinder of an ic engine based on the calculated or measured power output.

(7) Specific fuel consumption:

The fuel consumption characteristics of an engine are generally expressed in terms of specific fuel consumption in kilograms of fuel per KWh.

Sfc= fuel consumption per unit time / power

(8) Air-fuel ratio or fuel-air ratio:

Air fuel ratio is defined as the ratio of air and fuel of a mixture prepared for combustion. For example, if we have a mixture of methane and air which has the air fuel ratio of 17.5, it means that in the mixture we have 17.5 kg of air and 1 kg of methane.

(9) Calorific value:

The calorific value of the fuel is also called as the heat value of the fuel. It is defined as the amount of heat released by burning of unit quantity of the fuel.

2^{nd} CHAPTER
Air Compressor

Function:

The function of compressor is to take a definite quantity of fluid (usually gas or air) and deliver it at required pressure.

Industrial use of compressed air:

The compressed air finds application in the following fields:

1. It is widely employed for powering small engines, generally those of portable nature.

Compressed air is used in such diversified fields as:

(a) operating tools in factories:

(b) operating drills and hammers in road building

(c) excavating:

(d) tunneling and mining;

(e) starting diesel engines; and

(f) operating brakes on buses, trucks and trains.

2. A large quantity of air at moderate pressure is used in smelting of various metals such as melting iron, in blowing converters, and cupola work.

3. Large quantities of air are used in the air-conditioning, drying, and ventilation fields. In many of these cases, there is little resistance to the flow of air; and hence it does not have to be compressed (ie, measurably decreased in volume). For such cases fans serve the purpose of moving the air to the desired location. In other cases, particularly in drying work, there is appreciable resistance to the flow of air and a compressor of some sort is required to build up sufficient pressure to overcome the resistance to flow.

Classification of air compressor:

The air compressors may be classified in many ways, but the following are important the subject point of view

1. According to working

(a) Reciprocating compressors, and (b) Rotary compressors

2. According to action

(a) Single acting compressors, and (b) Double acting compressors

3. According to number of stages

(a) Single stage compressors, and (b) Multi-stage compressors

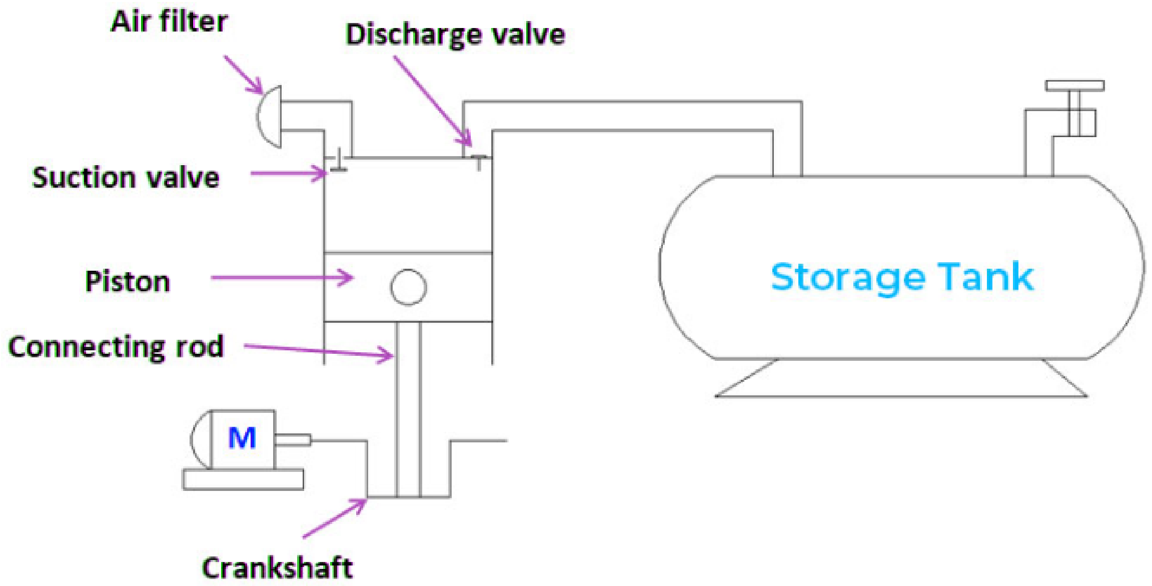
Reciprocating air compressor:

The reciprocating compressor is a positive displacement air compressor where the air is sucked in a chamber and it is compressed with a reciprocating piston by decreasing the area of the chamber.

Working principle:

In the reciprocating air compressor, the piston moves to BDC and air is sucked into a cylinder from the atmosphere and moves it to the TDC. The compression of air starts and increasing and pressure is also increasing. After reaching the limit of the pressure the discharge valve is open and the compressed air is flowing through to the storage tank.

Main parts:

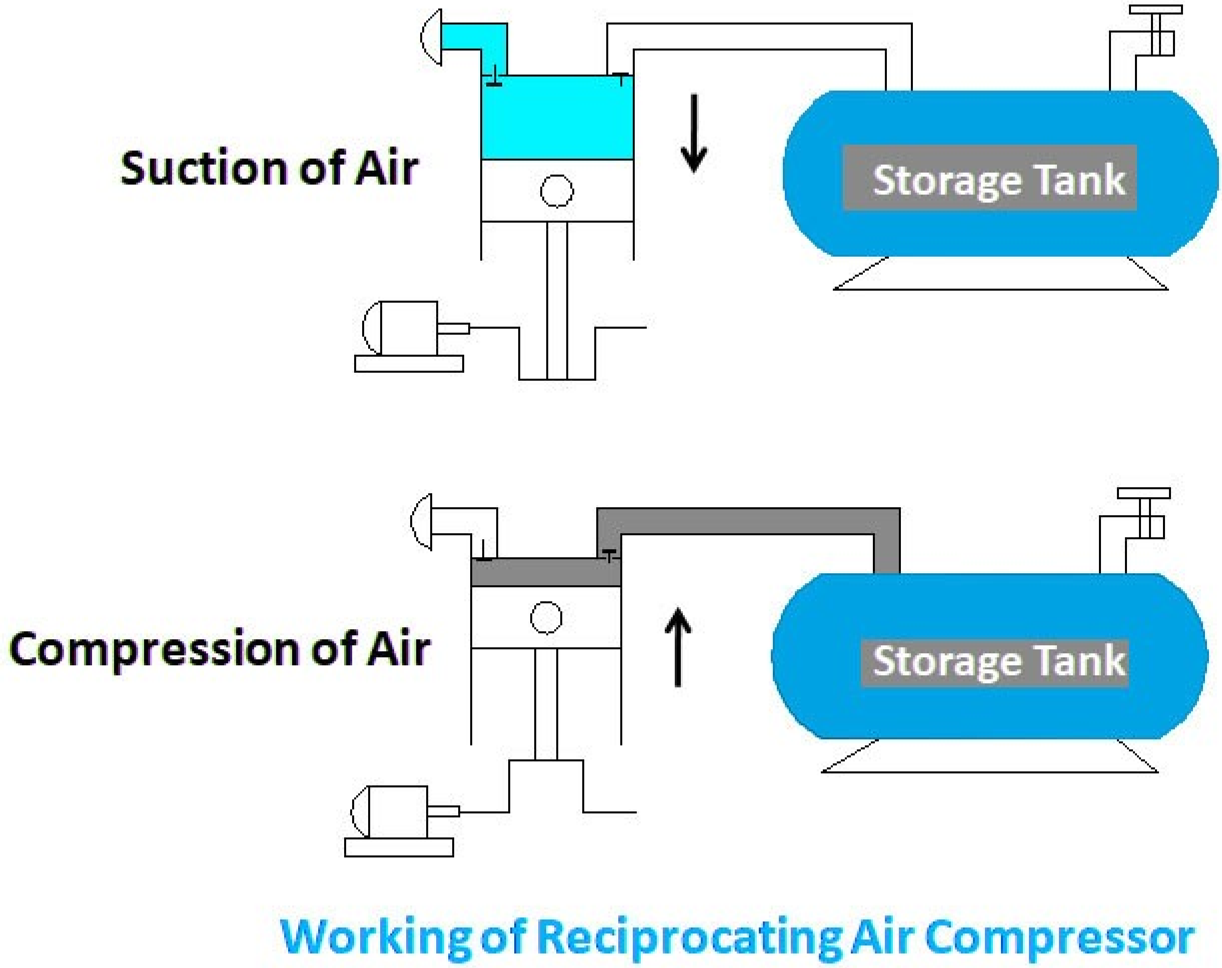


Main Parts of Reciprocating Air Compressor

Piston: It has reciprocating motion in the cylinder and it compresses the air.
Cylinder: The air is compressed in the cylinder.
Connection Rod: This connects the piston and crankshaft.
Crankshaft: This is connected to the shaft of the electric motor and transfers rotary motion to the piston.
Suction valve: Air is sucked through a suction valve when the piston moves to BDC.
Discharge valve: Compressed air is discharged through the discharge valve to the storage tank.

Working of reciprocating compressor:

The reciprocating air compressor is powered by an electric motor or by diesel/gas engines.



When the power in on, the electric motor starts rotating and rotates the crankshaft which attached to it and the piston starts moving the to and fro motion inside a cylinder.

The piston is moved downward the air from the atmosphere enters into the cylinder chamber.

After reaching to BDC the piston start moving upward and the compression of air starts and its pressure tends to increase.

After reaching the set pressure the discharge valve is open and through it, the compressed air is transfer to a storage tank where it can be used.

Technical terms:

(a) Bore:

It is defined as the ratio of the actual air capacity to the ideal air capacity. It is also the mass of air that enters in suction stroke to the mass of free air equivalent to the piston displacement at intake temperature and pressure conditions.

(b) Stroke:

The stroke length is how far the piston travels in the cylinder, which is determined by the cranks on the crankshaft.

(c) Pressure ratio:

It is the ratio of discharge pressure to the inlet pressure.

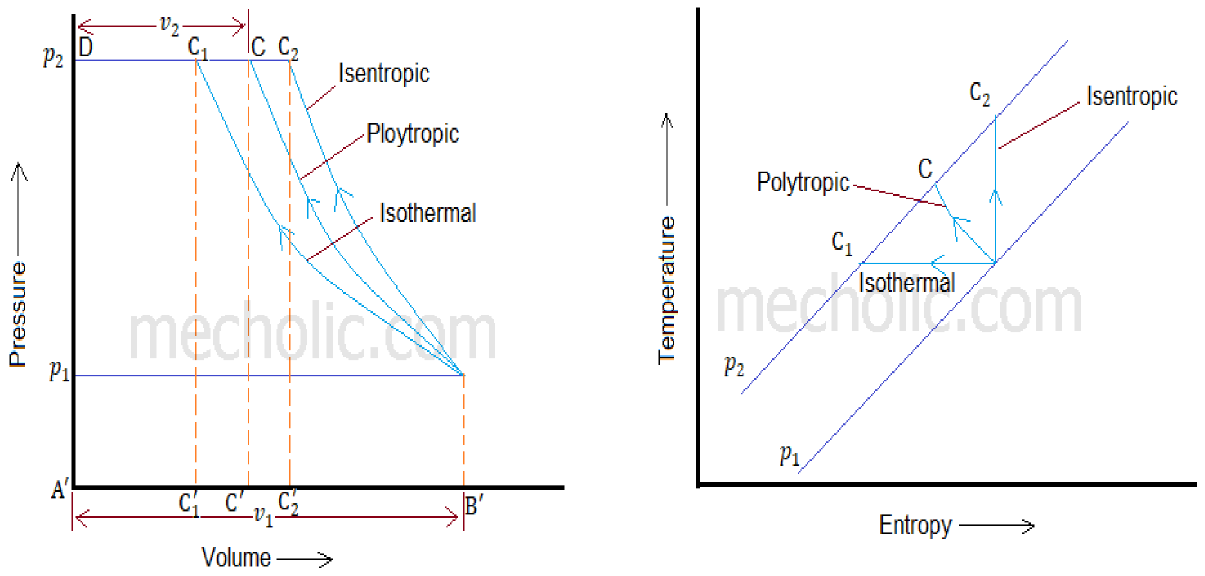
(d) Free air delivered:

Free air delivery is the volume of air delivered under the conditions of temperature and pressure existing at the compressor intake.

(e) Volumetric efficiency:

This is the ratio of the capacity of a compressor to the piston displacement of the compressor.

Work done of single stage reciprocating compressor without clearance:



(a) p-v Diagram (b) T-s diagram

The working of reciprocating compressor includes three operations, suction, compression, and discharge of compressed fluid. thus there are three work is included in a cycle of reciprocating compressor, work of piston during the suction of fluid/ refrigerant, work of piston during the compression of fluid as well as work during the discharge of compressed fluid. Mathematically the work done by the reciprocating compressor is equal to the work done by compressor during compression and discharge minus the work done during the suction of fluid.

Consider a single stage, single acting reciprocating compressor without clearance volume. The following figure shows the PV and TS diagram of this compressor.

The compression process may be isentropic, polytropic, or isothermal.

Let P_1 = Suction pressure (pressure before compression)
V_1 = Suction volume
T_1= Suction temperature,
P_2, V_2, T_2 are the corresponding pressure, volume, and temperature after compression. (r is compression ratio (p_1/p_2))

Work done during isothermal compression:

The line AB represents suction of fluid, area under AB (ie ABB'A') represent work done during the suction process

$W_1 = P_1V_1$

BC$_1$ represent compression of fluid when piston moving from bottom dead centre to top dead centre. When the pressure inside the cylinder reaches p_2, the discharge valve opens. Further movement piston towards the top dead centre cause the compressed air to discharge. C$_1$D represent discharging of fluid.

Work done during compression is W_2 = Area of BC$_1$C$_1$'B'
$W_2 = P_1V_1 \log_e (V_1/V_2)$
Work done during discharge W_3= Area C$_1$DA'C$_1$'
$W_3 = p_2v_2$
Work done by the compressor during the one complete cycle of operation is equal to W= $W_3+W_2-W_1$
$W = P_2V_2 + P_1V_1 \log_e (V_1/V_2) - P_1V_1$
Since $P_1V_1 = P_2V_2$
$W = P_1V_1 \log_e (V_1/V_2) = 2.3\, P_1V_1 \log (V_1/V_2)$
But $P_1V_1 = mRT_1$
$V_1/V_2 = P_2/P_1 = r$
$W = 2.3\, mRT_1 \log r$

Work done during polytropic compression (PV^n = constant)

The work done during the compression is equal to area under BCC'B'

$$W_2 = \frac{p_2v_2 - p_1v_1}{n-1}$$

Work done W= $W_3+W_2-W_1$

$$W = p_2v_2 + \frac{p_2v_2 - p_1v_1}{n-1} - p_1v_1$$

$$= \frac{(n-1)p_2v_2 + p_2v_2 - p_1v_1 - (n-1)p_1v_1}{n-1}$$

$$= \frac{n}{n-1}(p_2v_2 - p_1v_1)$$

$$= \frac{n}{n-1}p_1v_1\left(\frac{p_2v_2}{p_1v_1} - 1\right)$$

For polytropic compression $p_1v_1^n = p_2v_2^n$, n is ploytropic index

$$\frac{v_2}{v_1} = \left(\frac{p_1}{p_2}\right)^{\frac{1}{n}}$$

Put the value of v_2/v_1 in equation of work done

$$W = \frac{n}{n-1} p_1 v_1 \left(\frac{p_2}{p_1} \left(\frac{p_1}{p_2}\right)^{\frac{1}{n}} - 1 \right)$$

$$= \frac{n}{n-1} mRT_1 \left(\frac{p_2}{p_1} \left(\frac{p_2}{p_1}\right)^{\frac{-1}{n}} - 1 \right)$$

$$= \frac{n}{n-1} mRT_1 \left(\left(\frac{p_2}{p_1}\right)^{\frac{-1}{n}+1} - 1 \right)$$

$$= \frac{n}{n-1} mRT_1 \left(\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1 \right)$$

since

$$\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} = \frac{T_2}{T_1}$$

The above equation will become

$$= \frac{n}{n-1} mRT_1 \left(\frac{T_2}{T_1} - 1 \right)$$

$$W = \frac{n}{n-1} mR(T_2 - T_1)$$

Work done during isentropic compression:

The curve BC_2 Shows isentropic compression. The equation for work done during isentropic compression is similar to that of during polytrophic compression.

$$W = \frac{\gamma}{\gamma - 1} mR(T_2 - T_1)$$

Here γ is isentropic index.

since

and

$$c_p - c_v = R = c_p \frac{\gamma - 1}{\gamma}$$

Here c_p and c_v are specific heats

$$W = \frac{\gamma}{\gamma - 1} mc_p \left(\frac{\gamma - 1}{\gamma} \right) (T_2 - T_1)$$

$$W = mc_p(T_2 - T_1)$$

Workdone by Reciprocating Air Compressor with Clearance Volume

The p–v diagram of a single stage, single acting reciprocating air compressor with clearance volume (v_c) is shown in Fig. 9.2.

Though the compression and expansion of air may be isothermal, polytropic or isentropic, yet is assumed to be polytropic. We know that workdone by the compressor per cycle,

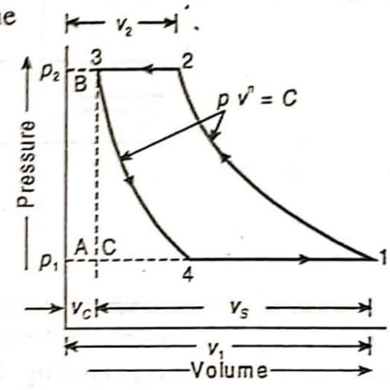


Fig. 9.2

$$W = \text{Area } 1\text{–}2\text{–}3\text{–}4$$

$$= \frac{n}{n-1} \times p_1 (v_1 - v_4) \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

$$= \frac{n}{n-1} \times mRT_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

where $(v_1 - v_4)$ and m is equal to the actual volume and mass of air sucked by the piston per cycle respectively. It may be noted that the clearance volume does not effect the workdone on the air and the power required for compressing the air.

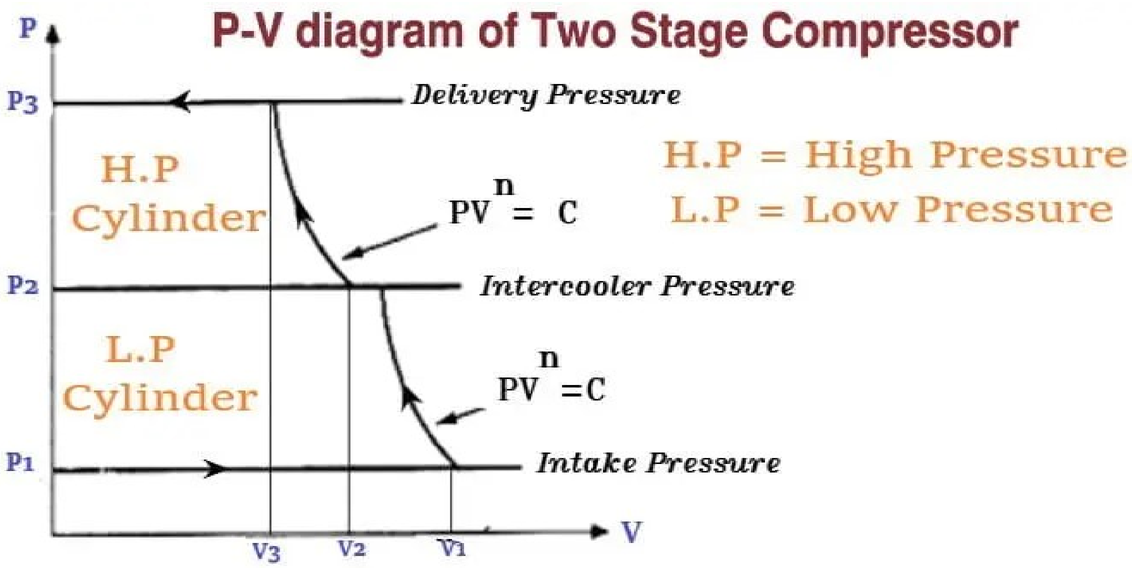
Two Stage Air Compressor:

A **2 stage air compressor** is a type of compressor which compresses the air in **two stages**. In this air compressor, the fluid compresses two times. It has two cylinders, and each cylinder has a piston. This air compressor uses two pistons. It uses one for compressing the air while the second piston uses to transfer the compressed air from one cylinder to the second cylinder.

These compressors use for high-pressure applications. The main difference between single-stage and 2-stage air compressors is that single-stage compressors complete the compression in only one stage while 2-stage air compressors complete compression in 2 stages.

2 Stage Air Compressor Working Principle:

This air compressor has a piston that connects with the crankshaft via a connecting rod. When the crankshaft rotates the piston, the piston moves forward and backward. The crankcase connects to the crankshaft. The inlet valve and outlet valve are connected to a cylindrical head which contains a valve cavity.



The above P-V diagram shows a two-stage air compressor. A **2 stage air compressor works** in the following way:

- As the prime mover coupled with the crankshaft starts rotating, the crankshaft also rotates. Due to the rotation of the crankshaft, the piston of the first cylinder (L.P cylinder) also starts its reciprocating motion.
- During this process, the piston sucks air through the suction valve and filter. The piston of the low pressure (L.P) cylinder compresses the air. The air in the L.P cylinder is compressed to an intermediate pressure "P2".
- After compressing the air to a specific degree, the piston of the L.P cylinder sends the compressed air into an intermediate pressure (I.P) air cooler where compressed air is cooled (as shown in the below-given diagram) before transferring it into the second (H.P) cylinder. The first stage compression ratio depends on the degree of cooling required.
- During the H.P cylinder's air compression process, the piston moves upward and downward and converts the air into high pressurized air. At last, the high pressurized air collects through the outlet valve.

Components of Two-stage Air Compressor:

The main components of the two-stage compressor are given below.

1. Inlet Valve
2. Intercooler
3. L.P Cylinder
4. H.P Cylinder
5. Outlet Valve

1) Inlet Valve or Suction Valve

The inlet valve uses for sucking the air from an external source into the compressor cylinder.

2) Cylinder

Cylinder uses for air compression. This type of compressor has two cylinders: a low-pressure cylinder and a high-pressure cylinder.

3) Piston

The piston uses to compress the air into the cylinder. It moves upward and downward into the cylinder. When it moves upward, it sucks the air into the cylinder while when it moves downward, it compresses the air. This piston air compressor has two pistons. Each cylinder has a piston.

4) Connecting Rod

The connecting rod connects the crankshaft and piston. The piston moves due to the movement of the connecting rod.

5) Intercooler

It uses to reduce the temperature of the air before sending it into the H.P cylinder. It cools the air.

6) Outlet Valve

It connects with the H.P cylinder. An outlet valve uses to discharge the compressed air.

3rd CHAPTER
Properties of steam

Difference between Vapour and Gas:

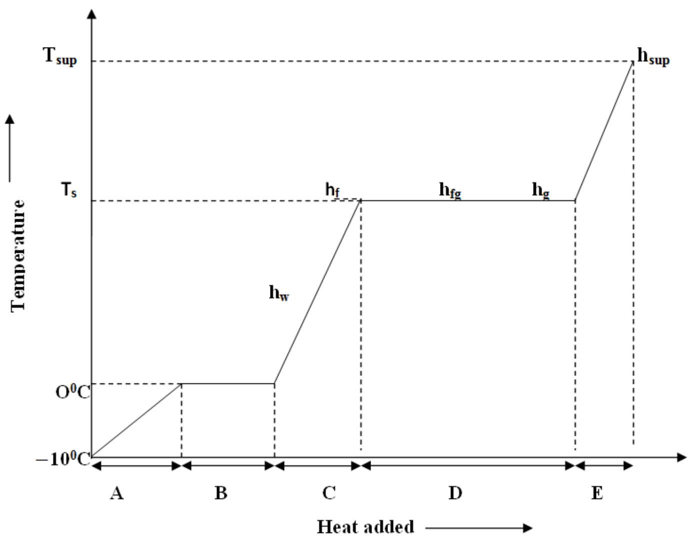
Usually, a vapour phase consists of a phase with two different substances at room temperature, whereas a gas phase consists of a single substance at a defined thermodynamic range, at room temperature. Thus, this is defined as the key differences between Vapour and Gas. You can find the major differences in the table below.

Difference between Vapour and Gas	
Vapour	Gas
Vapour is a mixture of two or more different phases at room temperature, these phases are liquid and gaseous phase.	Gas usually contains a single thermodynamic state at room temperature.
Vapour has a collection of particles without any definite shape when observed under a microscope.	Gas does not a definite shape when it is observed under a microscope.
Vapour consists of random molecules and atoms moving randomly about.	Gas also consists of random molecules and atoms moving about randomly.
Vapour is not a state of matter, unlike gases.	Gases are a state of matter.
Vapours of water are around us all the time at	Gases are usually formed above its critical

temperatures below the boiling point of water.	temperature, but below critical pressure.

Formation of Steam:

In general, steam can be formed by boiling water in a vessel. But to use it effectively as a working or heating medium, it has to produce in a closed vessel under pressure. Steam formed at a higher pressure has higher temperature and can be made to flow easily through insulated pipes from steam generator to point of use. A simple arrangement of formation of steam at constant pressure is shown in **Fig. a**.



A = Sensible Heat taken by Ice
B= Latent Heat of Fusion
C = Sensible Heat taken by Water
D = Latent Heat of evaporation
E = Sensible Heat taken by Steam
h_w = Specific enthalpy of water
h_f = Specific enthalpy of saturated water
h_{fg} = Latent heat of evaporation
h_g = Specific enthalpy of dry saturated steam
h_{sup} = Specific enthalpy of super heated steam
Fig. a Temperature enthalpy curve of formation of steam at constant pressure

Consider 1 kg of ice at temperature -10^0C which is below the freezing point. Let it be heated at constant pressure P. The temperature of ice starts increasing until it reaches the melting temperature of ice i.e., 0^0C and during this course ice absorbs its sensible heat. On further addition of heat, ice starts melting, its temperature remains constant at 0^0C and it absorbs latent heat of fusion and converts completely into water at 0^0C.

On further addition of heat, the temperature of water starts rising until it reaches the boiling temperature or saturation temperature corresponding to pressure P. This heat absorbed by water in sensible heat.

Note: Saturation temperature or boiling temperature increases with increase in pressure

After the boiling temperature is reached, it remains constant with further addition of heat and vaporization take place. The water absorbs its latent heat and converts into dry saturated steam remaining at same saturation temperature. The intermediate stage of water and dry saturated steam is wet steam, which is actually a mixture of steam and water.

If further the heat is added, the temperature of this dry saturated steam starts rising from saturation temperature and it converts into superheated steam. This heat absorbed is again the sensible heat. The total rise in temperature of superheated steam above the saturation temperature is called degree of superheat. We must know here that the saturation temperature, latent heat and other properties of steam remain same at constant pressure but varies with the variation of pressure.

Steam:

Steam is an invisible gas consisting of vaporized water, which is formed when water boils.

Qualities of Steam:

- Produced from water
- Clean, odorless, and tasteless
- Easily distributed and controlled
- Heat can be used over and over
- High usable heat content
- Gives up its heat at constant temperature
- Well-known characteristics
  - Pressure, temperature, volume

Properties of Steam:

The physical phenomenon of converting water from a liquid to a vapor (steam) is the same, whether it occurs on a stove with a tea kettle, in a small package boiler, or in a the most sophisticated high-pressure boiler in a power plant. Steam obeys a precise, well defined, documented set of physical laws.

Two atoms of hydrogen and one atom of oxygen make up one molecule of water (H_2O). The energy that the molecules of any substance possess is of two forms:

Kinetic energy - energy in motion

Potential energy – energy of position

When energy is added to a substance under conditions which **do not** change its state, the energy takes the form of motion (kinetic energy); and an increase in motion of molecules results in an increase in temperature. When energy is added to a substance under conditions which **do** change its state, the energy takes the form of change of position of the molecules (potential energy), and results in a change of state without any change in temperature.

In the case of steam, sensible heat has kinetic energy and latent heat has potential energy.

Types of Steam:

Steam is an invisible gas created by adding heat energy to water. It is liquid water changed to its gaseous state.

- **Saturated steam** - steam in immediate contact with the water from which it is being generated. If the pressure remains constant, any loss of heat or BTUs will result in condensation.

- **Superheated steam** – If more heat is added to dry saturated steam at a constant pressure, increasing its temperature and specific volume, superheated steam is produced. Heat must be lost, and temperature reduced before condensation occurs.
- **Flash steam** - when condensate, at saturation temperature and pressure, is discharged into a region of lower pressure, it automatically adjusts to the saturated conditions at the lower pressure. In effect, some of the condensate is "re-evaporated" into steam.

Flow process: It is one in which fluid enters the system and leaves it after work interaction, which means that such processes occur in the systems having open boundary permitting mass interaction across the system boundary.

Non-Flow process: Non-flow processes are thermodynamic processes in which there is no exchange of mass. Non-flow processes can exchange heat or work with their surroundings. There are four types of thermodynamic non-flow processes, i.e., isochoric, isobaric, isothermal, and adiabatic processes.