Introduction to compressors

- The machine which takes in air or any other gas at low pressure and compresses it to high pressure is called compressor. The compressor is power consuming machine in which mechanical work is converted into pressure energy of fluid. They are also considered as reversed heat engine.
COMPRESSORS

POSTIVE DISPLACEMENT

RECIROCATING
  SINGLE STAGE
  SINGLE ACTING

ROTARY
  MULTI STAGE
  DOUBLE ACTING

ROTO--DYNAMIC

TURBO COMPRESSOR
  RADIALFLOW (CENTRIFUGAL)
  MIXED FLOW
  AXIAL FLOW

EJECTOR
Positive displacement compressor

- Positive displacement compressors draw in and capture a volume of air in a chamber, then reduce the volume of the chamber to compress the air.

- Reciprocating Piston Compressors, Rotary Screw Compressors, Rotary Vane Compressors, and Scroll Compressors are all positive displacement compressors.
Non-positive displacement compressors, also called as steady flow compressors.

Use dynamic action of solid boundary for realizing pressure rise. Here fluid is not contained in definite volume and subsequent volume reduction does not occur as in case of positive displacement compressors.

Non-positive displacement compressor may be of ‘axial flow type’ or ‘centrifugal type’ depending upon type of flow in compressor.
## COMPARISON OF DIFFERENT COMPRESSORS

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Reciprocating compressors are widely used for compressing air and it is satisfactory for all ranges of pressures. The number of cylinders may be more than one. In single stage reciprocating compressor pressure ratio is kept 5 to 8, and the speed varies from 100 to 1500 rpm.
The single stage, single cylinder, single acting compressors consists of piston, cylinder, cylinder head, connecting rod, crank shaft, flywheel, crank case, water jacket, suction valve and delivery valve as shown in fig.
Advantages:

- Relatively Cheap.
- Easy maintenance.
- Suitable for high pressure.

Disadvantages:

- Sounds too much. One has to arrange a room for it or put it into isolating box.
- High outlet temperature of compressed air.
- High oil content in air piping.
Isentropic Compression

\[ W = \frac{\gamma}{\gamma - 1} p_1 V_1 \left\{ \left( \frac{p_2}{p_1} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right\} \]

polytropic compression

\[ W = \frac{n}{n - 1} p_1 V_1 \left\{ \left( \frac{p_2}{p_1} \right)^{\frac{n - 1}{n}} - 1 \right\} \]
**Isothermal compression**

\[ W = RT_1 \ln \left( \frac{p_2}{p_1} \right) \]

If compression process is isothermal, \( pV = C \), temperature remains constant, the change of internal energy during compression process is zero. Thus as per law of conservation of energy the entire work of compression is related to the cooling medium (surroundings). It is clear from for \( p-V \), the area 1-2’’-3-4 is less than area 1-2-3-4 and area 1-2’-3-4. It means that in isothermal compression no energy is wasted in heating the air or increasing the internal energy. It has been found that work required for compression is minimum when the process is isothermal.
Methods of cooling:

- Faster heat dissipation from inside of compressor to outside by use of fins over cylinder. Fins facilitate quick heat transfer from air being compressed to atmosphere so that temperature rises during compression can be minimized.

- Water jacket may be provided around compressor cylinder so that heat can be picked by cooling water circulating through water jacket.
The water may also be injected at the end of compression process in order to cool the air being compressed. This water injection near the end of compression process requires special arrangement in compressor and also the air gets mixed with water and needs to be separated out before being used.

In case of multistage compression in different compressors operating serially, the air leaving one compressor may be cooled up to ambient state or somewhat high temperature before being injected into subsequent compressor. This cooling of fluid being compressed between two consecutive compressors is called intercooling and is frequently used in case of multistage compressors.
Single stage reciprocating compressor with clearance:

- With clearance volume the cycle is represented on Fig. The work done for compression of air polytropically can be given by the area enclosed in cycle 1-2-3-4. **Clearance volume in compressors varies from 1.5% to 35% depending upon type of compressor.** In the cylinder of reciprocating compressor (V1-V4) shall be the actual volume of air delivered per cycle. $V_d = V_1 - V_4$. This ($V_1 - V_4$) is actually the volume of air inhaled in the cycle and delivered subsequently.
Reciprocating Compressor – Equation for Work

Clearance Volume:

Volume that remains inside the cylinder after the piston reaches the end of its inward stroke.

Thus, Effective Stroke Volume = $V_1 - V_4$

Actual Work = $W_{act} = \text{Area 1-2-3-4}$

$W_{act} = \text{Area (5-1-2-6)} - \text{Area (5-4-3-6)}$
Work done for polytropic:

\[ W = \frac{n}{n-1} p_1 (V_1 - V_4) \left\{ \left( \frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right\} \]

Volumetric efficiency:

\[ \eta_v = 1 - \frac{V_3}{V_1 - V_3} \left[ \frac{V_4}{V_3} - 1 \right] \]
The efficiency decreases with increase in the clearance ratio $C$. At $C = 0$, clearance volume $= 0$, efficiency $= 100\%$, no clearance is provided. When the value of $C$ and $r$ are constant, efficiency increases with $n$. 

$$\eta_v = 1 + C - C \left[ \left( \frac{P_2}{P_1} \right)^{\frac{1}{n}} \right]$$
Free Air Delivery (FAD):

- The free air delivery is the actual volume of air delivered by the compressor when it reduced to ambient pressure and temperature conditions. It is expressed in and represents the capacity of compressor. Following factors reduce the FAD less than swept volume and volumetric eff.
- The presence of clearance volume.
- The throttling of the air when it passes through the inlet and outlet valves.
- Heating of incoming air and
- Leakage.
Actual (indicator) diagram for single stage reciprocating compressor
Mean effective pressure

The area of indicated diagram represents the work done per cycle. The average height of the indicator diagram in proper unit of pressure is called the indicated mean effective pressure ($p_m$)

$$p_m = \frac{\text{Area of indicator diagram} \times \text{spring constant}}{\text{Length of indicator diagram}}$$

$$p_m = \frac{\text{workdone / cycle}}{\text{swept volume / cycle}}$$

$$p_m = \frac{n}{n-1} p_1 \eta_v \left\{ \left( \frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right\}$$
## Indicated power

The power consumed inside the cylinder, as measured from the indicator diagram is termed as the indicated power.

\[
\text{Indicated power (IP)} = \frac{\text{Work done / min}}{60 \times 1000} \text{ kW}
\]

But, work done = \( p_m \times L.A.N \times (x \times i), \text{Nm} \)

\[
\therefore \text{IP} = \frac{p_m \times L.A.N}{60 \times 1000} \times (x \times i), \text{ in kW}
\]

\( x = \text{no. of cylinders per stage} \)
\( i = 1 \) for single acting
\( i = 2 \) for double acting
Compressor efficiencies

• Mechanical efficiency \( (\eta_m) \): It is ratio of Indicated power (IP) to the Brake power (BP) of compressor. The power required to drive the compressor is called the brake power or shaft power of the compressor.

\[
B.P = \frac{2\pi NT}{60000}, kW
\]

\[
\eta_m = \frac{I.P.}{B.P}
\]

It varies from .85 to .96.
• Isothermal efficiency ($\eta_{iso}$): It is the ratio of isothermal work input (minimum work input) to actual work input (polytropic work input).

$$\eta_{iso} = \frac{\text{isothermal work input}}{\text{actual work input}}$$

$$= \frac{p_1 V_1 \ln \left( \frac{p_2}{p_1} \right)}{\frac{n}{n-1} p_1 V_1 \left( \left( \frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right)}$$

It is 100% when compression process is isothermal (best because compressor needs minimum work).
• Adiabatic efficiency ($\eta_{ad}$): It is the ratio of actual work input to adiabatic work input.

\[
\eta_{ad} = \frac{\text{Actual work input}}{\text{Adiabatic work input}}
\]

\[
= \frac{\frac{n}{n-1} p_1 V_1 \left\{ \left( \frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right\}}{\frac{Y}{Y-1} p_1 V_1 \left\{ \left( \frac{p_2}{p_1} \right)^{\frac{Y-1}{Y}} - 1 \right\}}
\]
In single stage compressor, entire compression of air takes place in single stroke of the piston. In multi stage compressor, compression takes in stages. For maximum compressor efficiency, it is desirable to cool air after one stage using inter-stage cooler. In two stage compressor, initial compression takes place in the low pressure cylinder. Air from this stage (low pressure cylinder) is passed through the inter cooler to reduce the temperature. Then the cooled air is compressed in the high pressure cylinder.
Advantages of multi-stage compression

- The work done in compressing the air is reduced, thus power can be saved.
- Prevents mechanical problems as the air temperature is controlled.
- The suction and delivery valves remain in cleaner condition as the temperature and vaporization of lubricating oil is less.
- The machine is smaller and better balanced.
- Effects from moisture can be handled better, by draining at each stage.
- Compression approaches near isothermal.
Disadvantages:

A multi-stage compressor is more expensive in initial cost than same capacity single stage reciprocating compressor. This is due to multi-stage compressor needs more than one cylinder, intercoolers with water supply system.
C. Two – Stage Compressor (With Perfect Intercooling):

With Intercooling:

L.P. : 8-1-4-7-8
H.P. : 7-2-3-6-7

Now,

\[ T_2 = T_1 \]

\[ P_2 V_2 = P_1 V_1 \]

Also

\[ P_4 = P_2 \]

\[ W = \frac{n}{n-1} P_1 V_1 \left[ 2 - \left( \frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - \left( \frac{P_3}{P_2} \right)^{\frac{n-1}{n}} \right] \]

Shaded Area 2-4-5-3-2 : Work Saving due to Intercooler...!!
The PV diagram for two stage compressor is shown in the Figure.
Work done per cycle in LP cylinder

\[ W_{LP} = \frac{n p_1 V_1}{n - 1} \left[ \left(\frac{p_2}{p_1}\right)^{n-1} - 1 \right] \]

Work done per cycle in HP cylinder

\[ W_{HP} = \frac{n p_2 V_2}{n - 1} \left[ \left(\frac{p_3}{p_2}\right)^{n-1} - 1 \right] \]

If the intercooling is perfect then \( p_1 V_1 = p_2 V_2 \)

\[ W = \frac{n p_1 V_1}{n - 1} \left[ \left(\frac{p_2}{p_1}\right)^{n-1} + \left(\frac{p_3}{p_2}\right)^{n-1} - 2 \right] \]

Condition for minimum power in two stage compressor with perfect intercooling is given by

\[ p_2 = \sqrt{p_1 p_3} \]

For a \( N \) stage compressor with perfect intercooling, compressing air from \( p_1 \) to \( p_{N+1} \)

\[ W = \frac{N n p_1 V_1}{n - 1} \left[ \left(\frac{p_{N+1}}{p_1}\right)^{n-1} - 1 \right] \]
Condition for minimum work or maximum efficiency

The work required per cycle for the above two stage reciprocating compressor without clearance and perfect intercooling is given by:

\[ W = \frac{n}{n-1} p_1 V_1 \left\{ \left( \frac{p_2}{p_1} \right)^{\frac{n-1}{n}} + \left( \frac{p_3}{p_2} \right)^{\frac{n-1}{n}} - 2 \right\} \]

The work input will be minimum when \( \frac{dW}{dp_2} = 0 \)

\[ \frac{p_3}{p_2} = \frac{p_2}{p_1} \]

, pressure ratio per stage is equal

\[ \therefore p_2 = \sqrt{p_3 \cdot p_1} \]
Minimum work required for two stage compressor

\[ W_{\text{min}} = \frac{2n}{n-1} p_1 V_1 \left\{ \left( \frac{p_3}{p_1} \right)^{\frac{n-1}{2n}} - 1 \right\} \]

If there are N numbers of stages, then condition of minimum work required is

\[ \frac{p_2}{p_1} = \frac{p_3}{p_2} = \frac{p_4}{p_3} = \ldots = \frac{p_{N+1}}{p_N} = z \text{ say} \]

\[ z = \frac{p_2}{p_1} = \left( \frac{p_{N+1}}{p_1} \right)^{\frac{1}{N}} = \left( \text{pressure ratio through compressor} \right)^{\frac{1}{N}} \]

\[ \therefore W_{\text{min}} = \frac{Nn}{n-1} p_1 V_1 \left\{ \left( \frac{p_{N+1}}{p_1} \right)^{\frac{n-1}{Nn}} - 1 \right\} \]
Following conditions are necessary for compressing air with minimum work input in a multi-stage compressor with intercooler:

• Compression ratio in each stage is equal.
• Air is cooled to initial temperature after each stage of compression.
• Work required in all stages is equal.
Actual p-V (indicator) diagram for two stage compressor
THANK YOU