Nawab Shah Alam Khan College of Engineering & Technology

Applied Thermodynamics

Department of
Mechanical Engineering

Course Objectives

- To study the application of thermal science in mechanical engineering, consisting of the fundamental laws and processes for energy conversion
- To understand thermal design aspects of reciprocating machinery-reciprocating compressors and IC Engines.
- To analyze Rankine cycle applied to thermal power plants and its improvements.
- To gain the knowledge on the power plant thermal Devices-Boilers, Condensers, Pumps &Nozzles.

Course Outcomes

1. Expected to be able to quantify the behavior of reciprocating compressors.
2. Expected to be able to explain thermal design and working principles of IC Engines, their supporting systems and Combustion chambers.
3. Expected to be able to quantify the behavior of power plants based on the Rankine cycle, including the effect of enhancements such as superheat, reheat and regeneration.

Course Outcomes

4. Expected to be able to explain the thermal design and working principles of Power plant devices.
5. Expected to be able to explain working principles of Boilers, Condensers, Pumps &Nozzles.

Syllabus

Unit I

Reciprocating Air Compressors:

- Classification and applications.
- Ideal and actual P-V diagrams
- Work input and efficiency relations for single and multi-stage compressors.
- Effect of clearance volume on work input and efficiency.
- Inter cooling and after cooling concepts.

Syllabus

- **Unit II - Internal Combustion Engines**
- **Unit III - I.C. Engine Combustion phenomena**
- **Unit IV - Steam Boilers, Steam Condensers**
- **Unit V - Steam Power Plant Cycles, Steam Nozzles**

Suggested Reading

- R.K. Rajput, " Thermal Engineering”, Laxmi Publications, 9th Edn., 2013
- V. Ganesan, "Internal Combustion Engines", Tata McGraw Hill Publishing, 2007
- P.L. Ballaney, "Thermal Engineering", Khanna Publishers, 19th Edn., 1993.
- Richard Stone, “Introduction to I.C. Engines”, Mac Millan, 2nd Edn., 1997

Reciprocating Air Compressors

Air Compressors

COMPRESSOR – ***A device which takes a definite quantity of fluid (usually gas, and most often air) and delivers it at a required higher pressure.***

Air Compressor – 1) Takes in atmospheric air,

2) Compresses it, and

3) Delivers it to a storage vessel (i.e. Reservoir).

Compression requires Work to be done on the gas,

$\Rightarrow$ **Compressor must be driven by some sort of Prime Mover (i.e. Engine / Motor)**

How they are different from pumps?

- Major difference is that compressors handle gases and pumps handle liquids.
- As gases are compressible, the compressor also reduces the volume of a gas.
- Liquids are relatively incompressible; while some can be compressed.

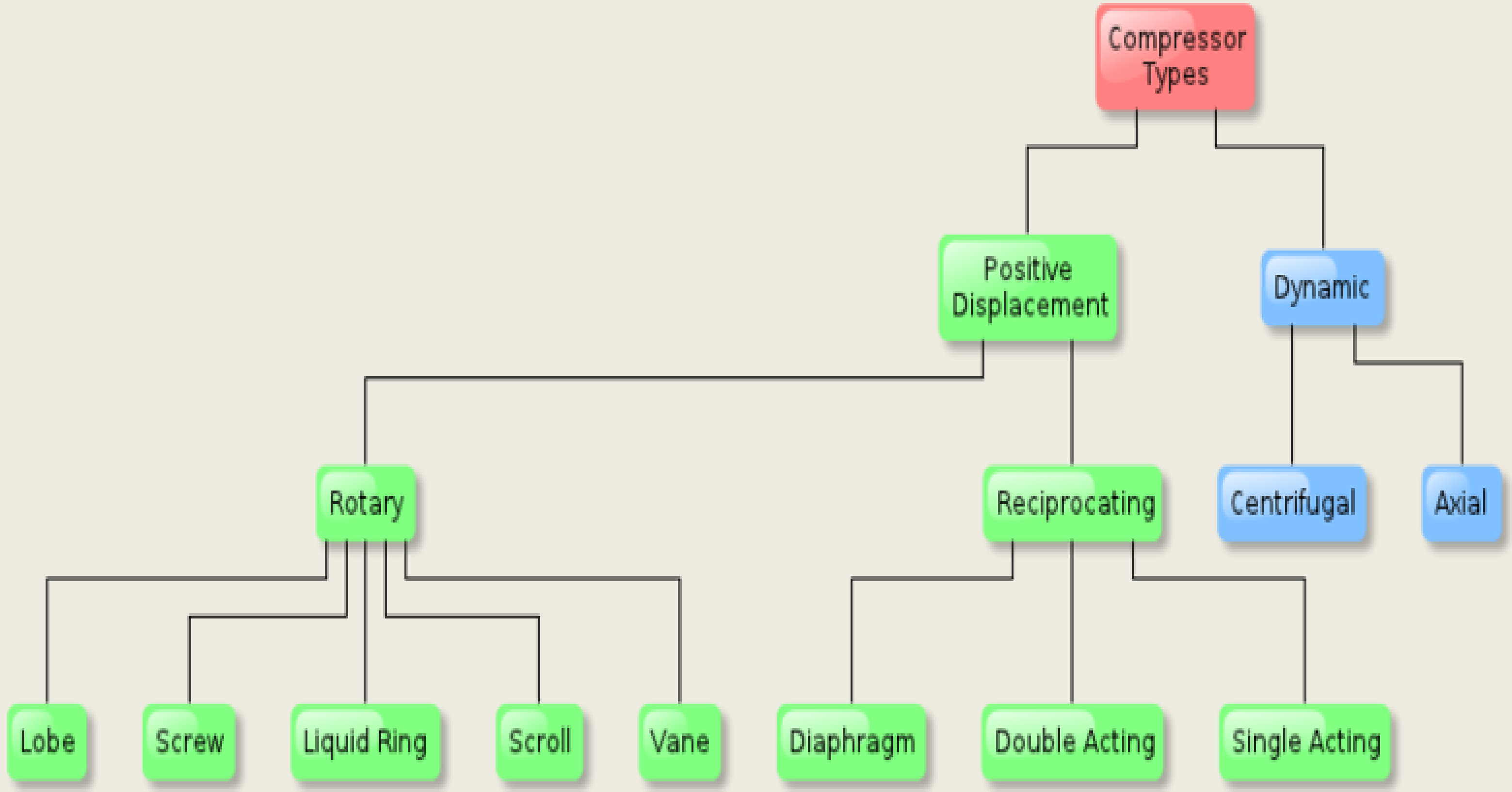
Applications

Compressors have many everyday uses, such as in :

- Air conditioners, (car, home)
- Pneumatic devices
- Home and industrial refrigeration
- Hydraulic compressors for industrial machines
- Air compressors for industrial manufacturing

Classification of Compressor

Compressor classification can be described by following flow chart:



Dynamic Compressors

The dynamic compressor is a continuous flow compressor and is characterized by rotating impeller to add velocity and thus pressure to fluid.

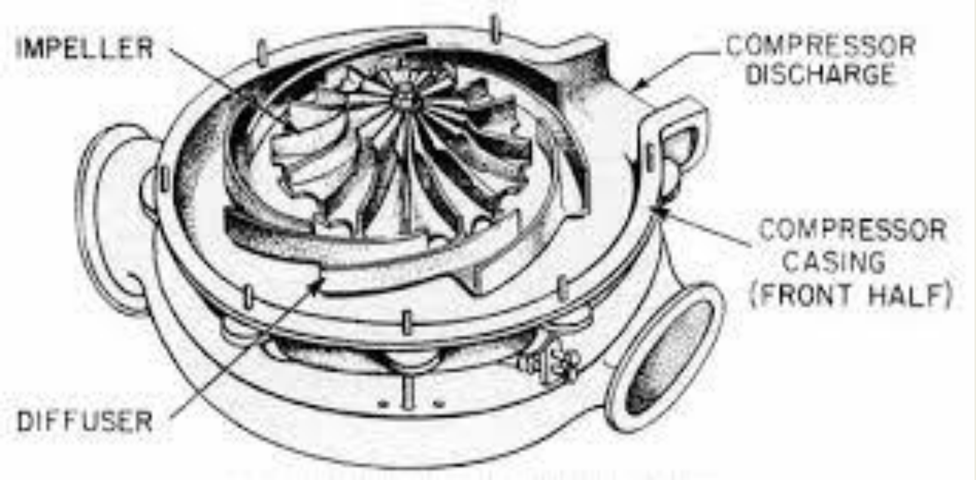
It is widely used in chemical and petroleum refinery industry for specific services.

There are two types of dynamic compressors

- Centrifugal Compressor
- Axial Flow Compressor

Centrifugal Compressors

- Achieves compression by applying inertial forces to the gas by means of rotating impellers.
- It is multiple stage ; each stage consists of an impeller as the rotating element and the stationary element, i.e. diffuser
- Fluid flow enters the impeller axially and is discharged radially
- The gas next flows through a circular chamber (diffuser), where it loses velocity and increases pressure.

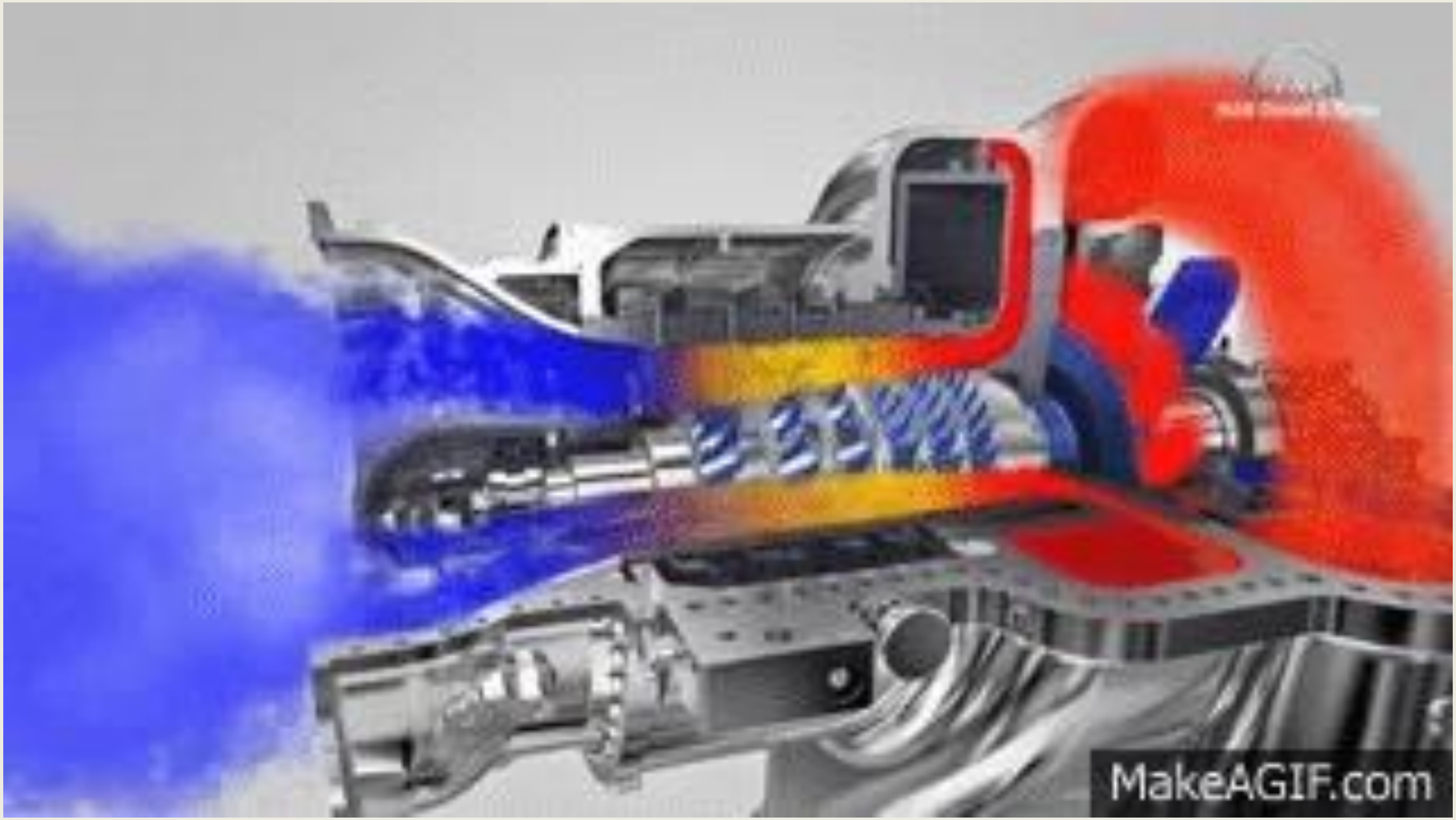


Centrifugal Compressors

Axial Flow Compressor

- Working fluid principally flows parallel to the axis of rotation.
- The energy level of air or gas flowing through it is increased by the action of the rotor blades which exert a torque on the fluid
- Have the benefits of high efficiency and large mass flow rate
- Require several rows of airfoils to achieve large pressure rise making them complex and expensive

Axial Flow Compressor



Positive displacement Compressor

Positive displacement compressors work by trapping a fixed amount of air in a chamber and then reducing the volume of the chamber to compress the air.

It can be further classified according to the mechanism used to move air.

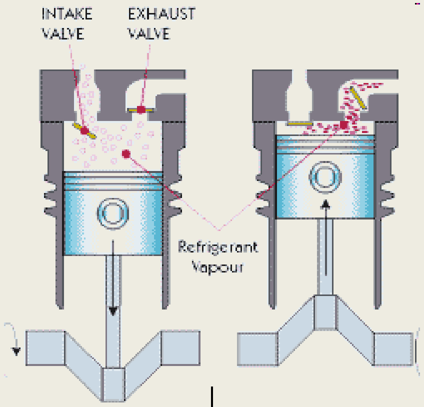
- Rotary Compressor
- Reciprocating compressor

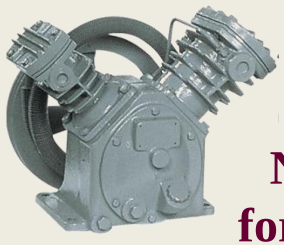
Positive displacement Compressor

Air Compressors

Reciprocating

Rotary





No. of Stages for Compression

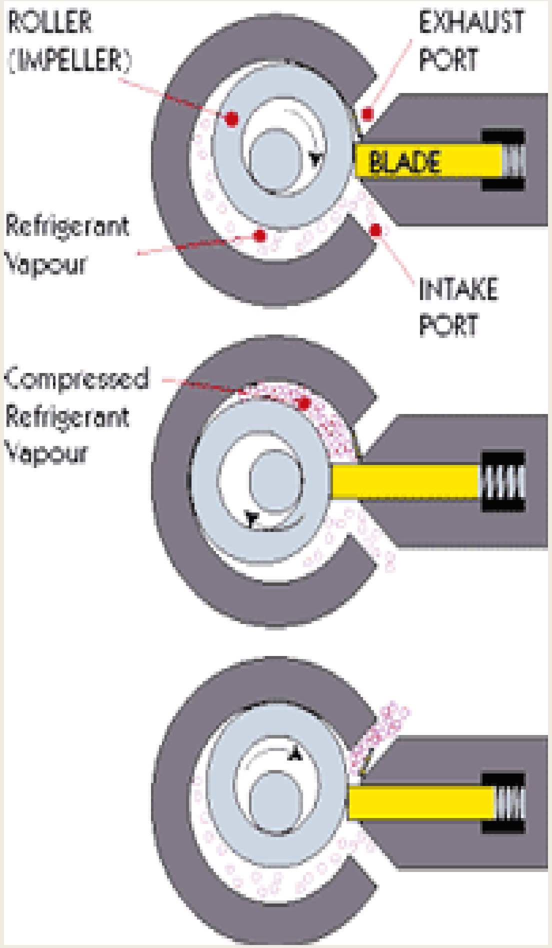
Single – stage
Multi - stage

No. of Sides of Piston in operation

Single – acting
Double - Acting

Rotary Compressor

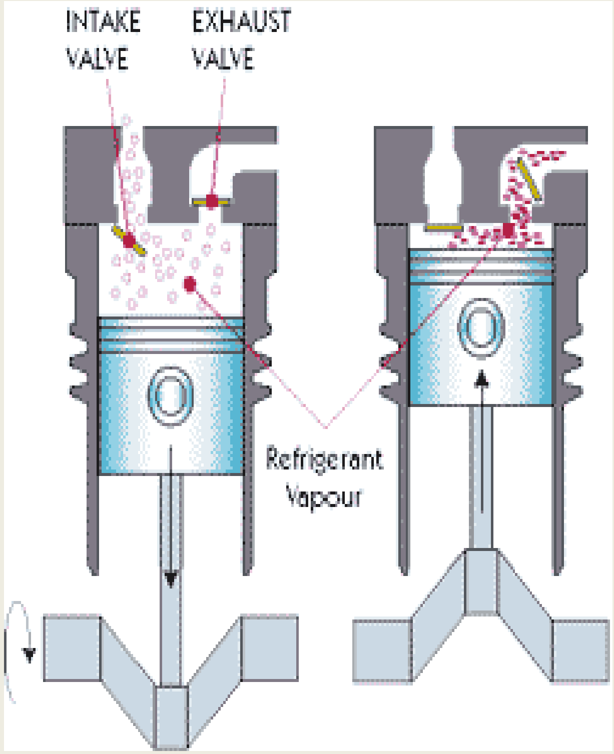
- The gas is compressed by the rotating action of a roller inside a cylinder.
- The roller rotates off-centre around a shaft so that part of the roller is always in contact with the cylinder.
- Volume of the gas chamber is reduced and the gas is compressed.
- Highly efficient as suction and compression of gas occur simultaneously.



Reciprocating Compressor

It is a positive-displacement compressor that

- Uses pistons driven by a crankshaft to deliver gases at high pressure.
- The intake gas enters the cylinder through suction manifold, then flows into the compression chamber
- It gets compressed by a piston driven in a reciprocating motion via a crankshaft,
- Discharged at higher pressure



Important Terms

- **Inlet Pressure:** Absolute pressure of air at the inlet of the compressor.

- **Discharge Pressure**: Absolute pressure of air at the outlet of compressor.

- **Compression Ratio** (Pressure Ratio): Ratio of discharge pressure to inlet pressure. Always more than unity.

- **Compressor Capacity**: Volume of air delivered by compressor. Expressed in m^3/min or m^3/s.

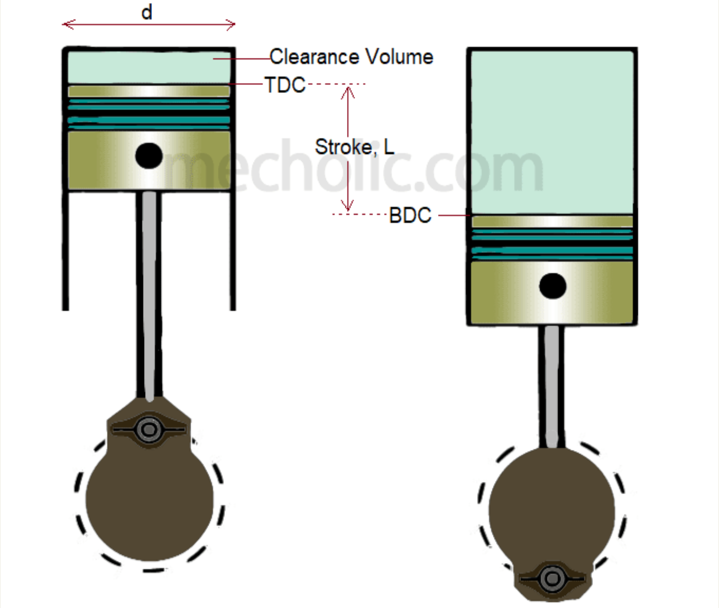
- **Free air delivery**: Actual volume of air delivered by a compressor when reduced to the normal temperature and pressure condition. Capacity of compressor is generally given in terms of free air delivery.

Important Terms

- **Swept Volume**: Volume of air sucked by the compressor during its suction stroke. Swept volume or displacement volume of single acting air compressor is given by

$$V_s = \frac{\pi}{4} \times D^2 \times L$$

Where D = Diameter of cylinder bore,
L = Length of piston stroke.



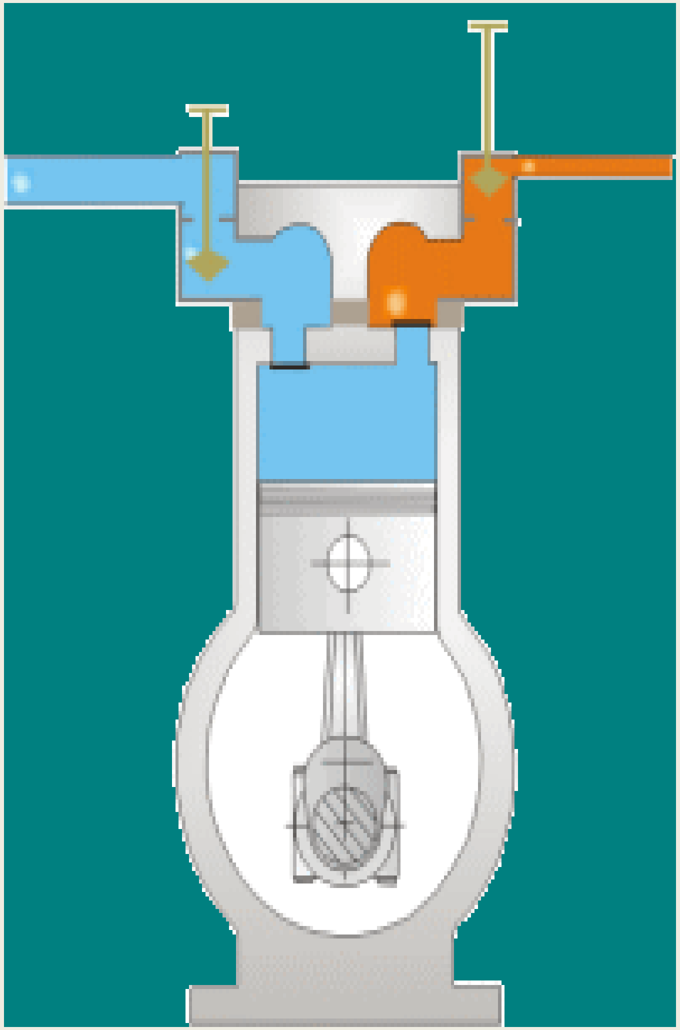
- **Mean effective pressure**: Air pressure on the compressor piston keeps on changing with the movement of piston in cylinder. Mean effective pressure is found out by dividing work done per cycle to swept volume.

$$P_m = \frac{Indicated\ work\ done\ per\ cycle}{swept\ volume\ of\ cylinder}$$

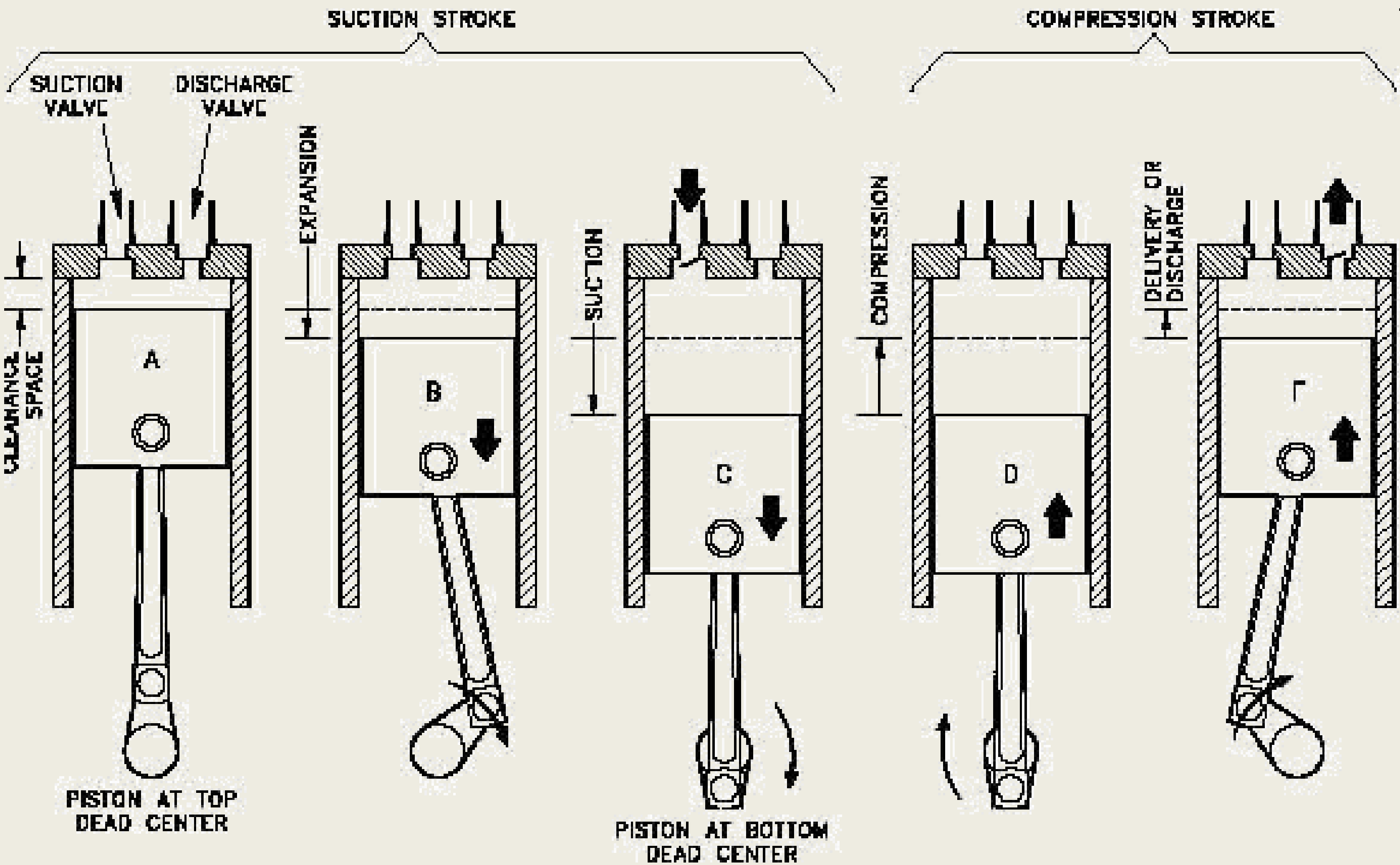
Reciprocating Compressor - Detailed Analysis

Principle of Operation

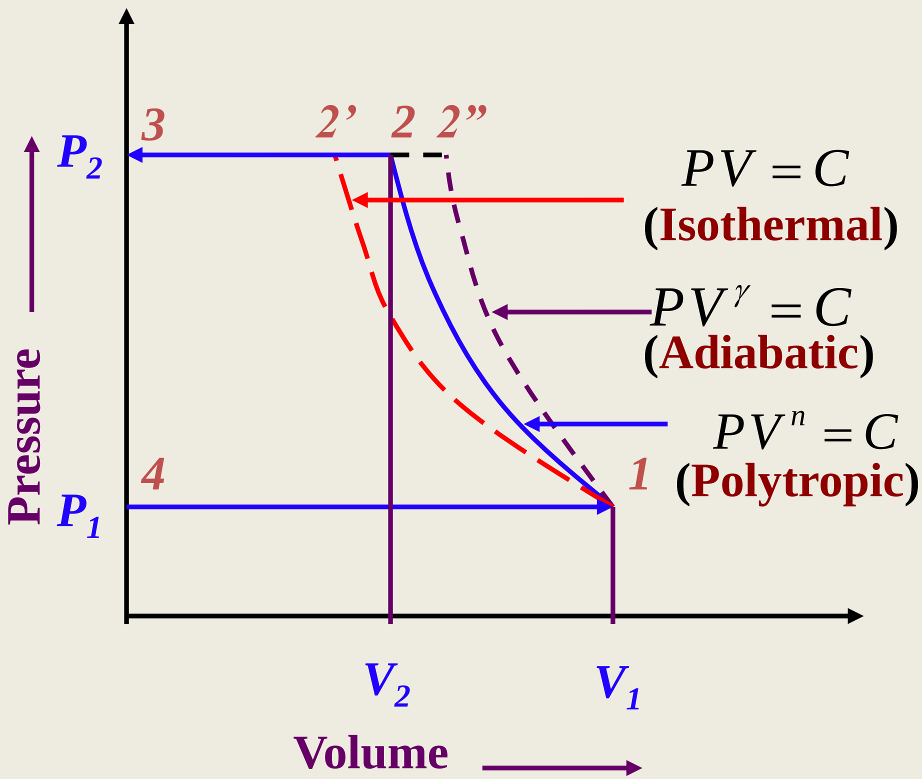
- Fig. shows single-acting piston movement in the cylinder of a reciprocating compressor.
- The piston is driven by a crank shaft via a connecting rod.
- At the top of the cylinder is a suction valve and a discharge valve.
- The valves are opened because of pressure difference.
- Reciprocating compressors can have multiple stages of compression.

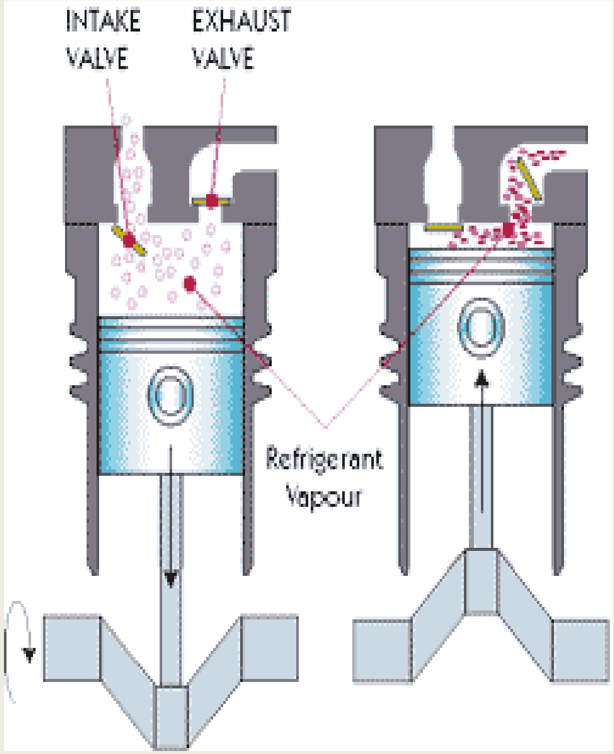


Reciprocating Compressor - Working



Reciprocating Compressor – Equation for Work





Operations **: 4 – 1 : Volume V_1 of air aspirated into Compressor, at P_1 and T_1.**

1 – 2 : Air compressed according to $PV^n = Const$. from P_1 to P_2.

$\longrightarrow$ Temp increase from T_1 to T_2.

2 – 3 : Compressed air at P_2 and V_2 with temperature T_2 is delivered.

Reciprocating Compressor – Equation for Work

During Compression, due to the excess temperature above surrounding, the air in cylinder will lose some heat to the surrounding.

$\Longrightarrow$ Compression Index, *n* is always less than γ, the adiabatic index.

As Compressor is a work consuming device, every effort is made to reduce the work input

Work done = Area under *P-V* curve

$\Longrightarrow$ 1 – 2" : Adiabatic Compression = Max. Work.

$\Longrightarrow$ 1 – 2 : Polytropic Compression

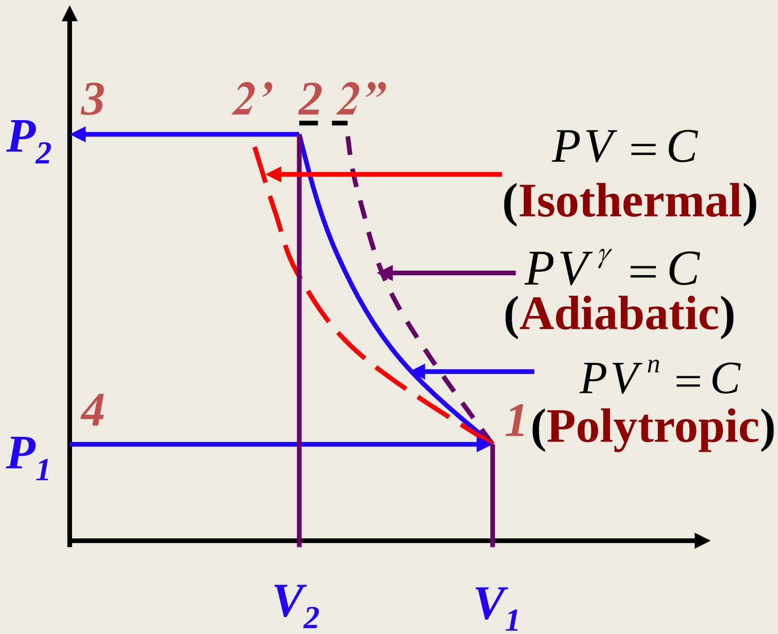
$\Longrightarrow$ 1 – 2' : Isothermal Compression = Min. Work.

Reciprocating Compressor – Equation for Work

Thus, comparison between the Isothermal Work and the Actual Work is important.

Isothermal Efficiency, $\eta_{iso} = \dfrac{\text{Isothermal Work}}{\text{Actual Work}}$

Thus, more the Isothermal Efficiency, more the actual compression approaches the Isothermal Compression.



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

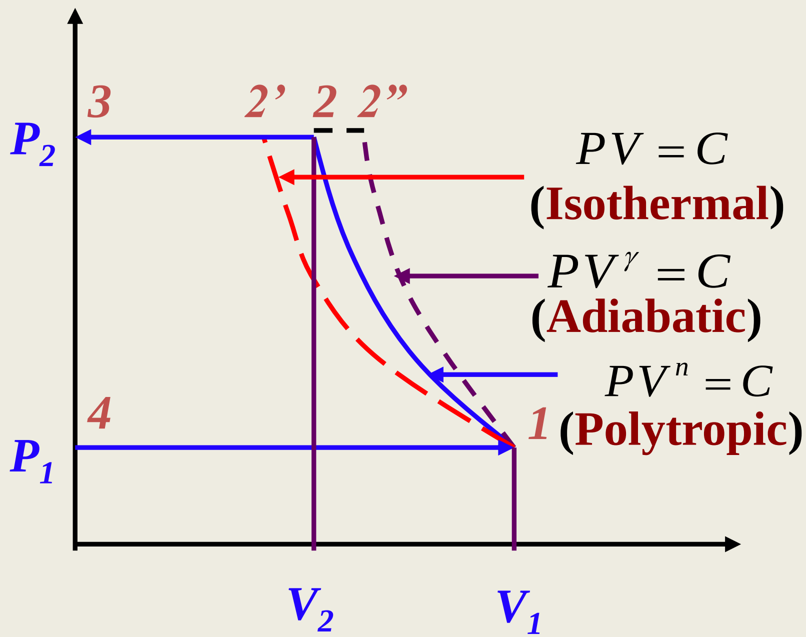
W_{act} = Area (4-1) – Area (1-2) – Area (2-3)

$$= P_1V_1 - \frac{P_2V_2 - P_1V_1}{n-1} - P_2V_2$$

$$= \left(P_1V_1 - P_2V_2\right) - \left(\frac{P_2V_2 - P_1V_1}{n-1}\right)$$

$$= \left(P_1V_1 - P_2V_2\right) + \left(\frac{P_1V_1 - P_2V_2}{n-1}\right)$$

Reciprocating Compressor – Equation for Work



$$W = \left(1 + \frac{1}{n-1}\right)\left(P_1V_1 - P_2V_2\right)$$

$$= \left(\frac{n}{n-1}\right)\left(P_1V_1 - P_2V_2\right)$$

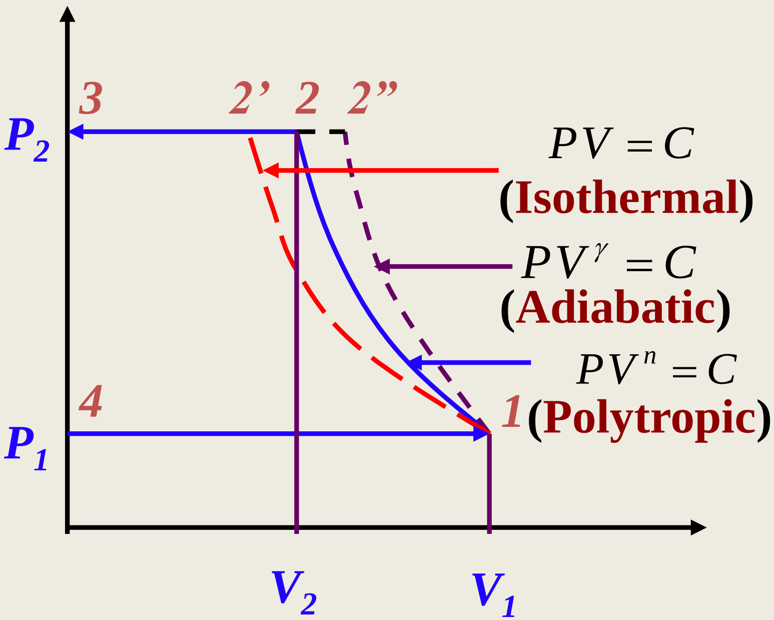
$$= \left(\frac{n}{n-1}\right) P_1V_1\left(1 - \frac{P_2V_2}{P_1V_1}\right)$$

Now, $P_1V_1^{\,n} = P_2V_2^{\,n}$

$$\Rightarrow \quad \frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{1/n}$$

$$W = \left(\frac{n}{n-1}\right) P_1V_1\left\{1 - \frac{P_2}{P_1}\left(\frac{P_1}{P_2}\right)^{1/n}\right\}$$

Reciprocating Compressor – Equation for Work



$$W = \left(\frac{n}{n-1}\right) P_1 V_1 \left\{1 - \frac{P_2}{P_1}\left(\frac{P_1}{P_2}\right)^{1/n}\right\}$$

$$= \left(\frac{n}{n-1}\right) P_1 V_1 \left\{1 - \frac{P_2}{P_1}\left(\frac{P_2}{P_1}\right)^{-1/n}\right\}$$

$$W = \left(\frac{n}{n-1}\right) P_1 V_1 \left\{1 - \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}\right\}$$

$$W = \left(\frac{n}{n-1}\right) mRT_1 \left\{1 - \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}\right\}$$

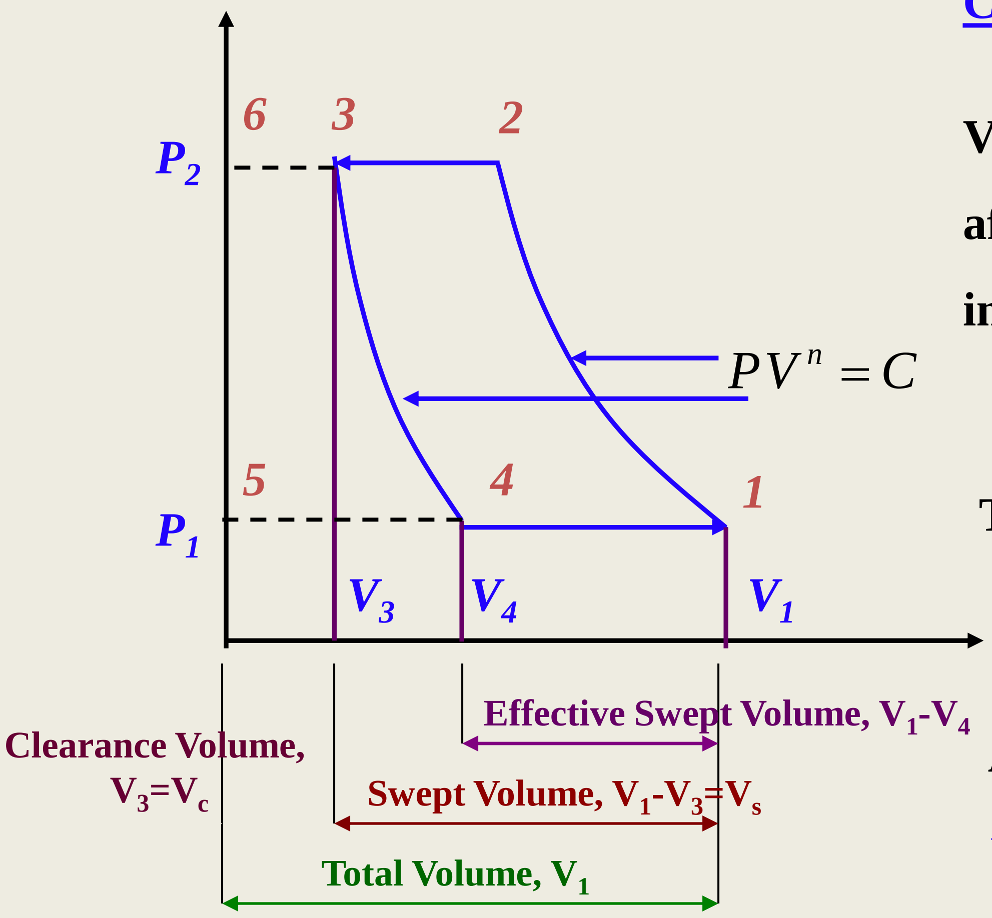
Delivery Temperature,

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

The solution of this equation is always *negative*.

This shows that Work is done *ON* the Compressor.

Reciprocating Compressor – Equation for Work



Clearance Volume :

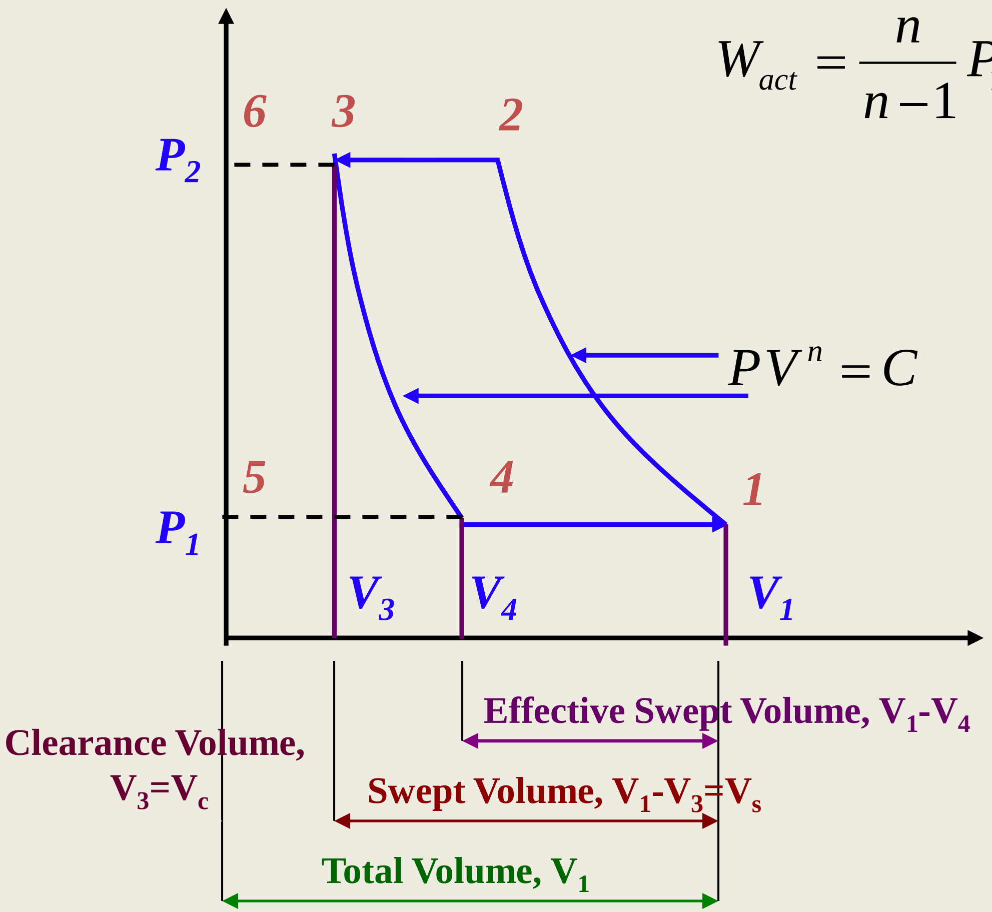
Volume that remains inside the cylinder after the piston reaches the end of its inward stroke.

Thus, *Effective Stroke Volume* = $V_1 - V_4$

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

W_{act} = Area (5-1-2-6) – Area (5-4-3-6)

Reciprocating Compressor – Equation for Work



$$W_{act} = \frac{n}{n-1} P_1 V_1 \left\{ 1 - \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \right\} - \frac{n}{n-1} P_4 V_4 \left\{ 1 - \left(\frac{P_3}{P_4} \right)^{\frac{n-1}{n}} \right\}$$

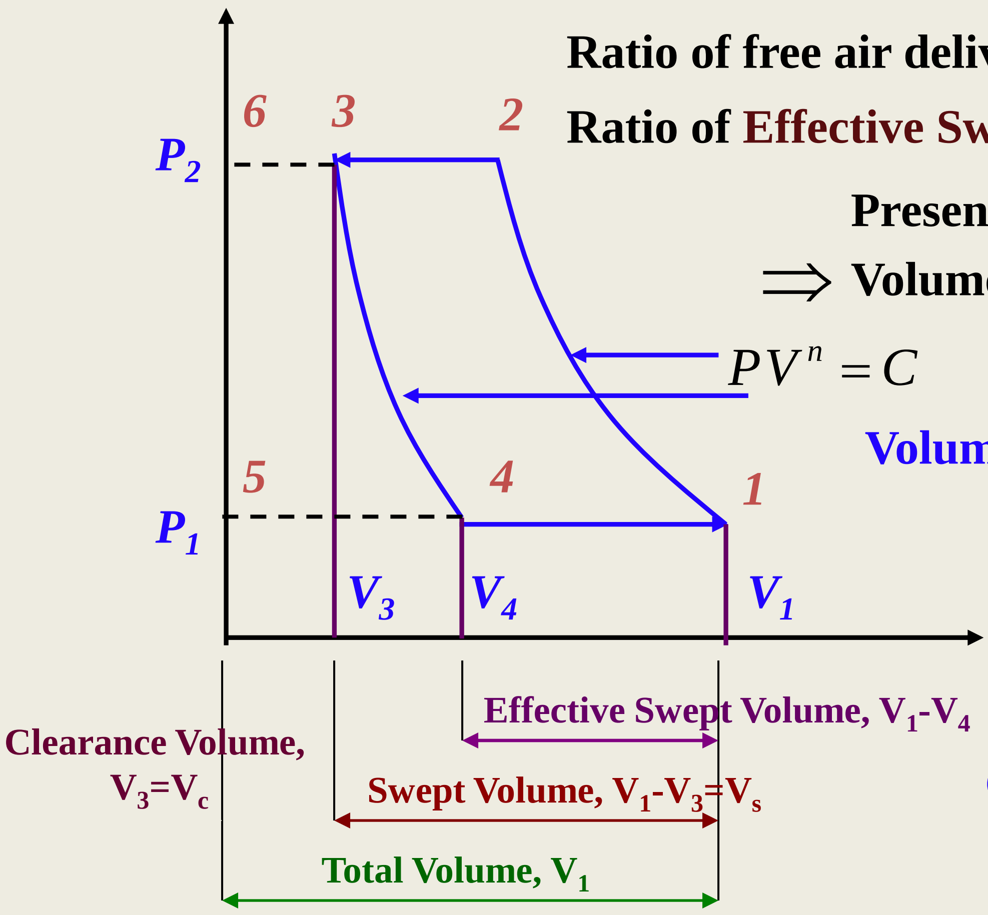
But, $P_4 = P_1$ and $P_3 = P_2$

$$\Rightarrow \quad W_{act} = \frac{n}{n-1} P_1 V_1 \left\{ 1 - \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \right\}$$

$$- \frac{n}{n-1} P_1 V_4 \left\{ 1 - \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \right\}$$

$$W_{act} = \left(\frac{n}{n-1} \right) P_1 \left(V_1 - V_4 \right) \left\{ 1 - \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \right\}$$

Reciprocating Compressor – Volumetric Efficiency



Volumetric Efficiency :

Ratio of free air delivered to the displacement of the compressor.

Ratio of Effective Swept Volume to Swept Volume.

Presence of Clearance Volume

$\Longrightarrow$ **Volumetric Efficiency less than 1. (60 – 85 %)**

$$\text{Volumetric Efficiency} = \frac{\text{Effective Swept Volume}}{\text{Swept Volume}} = \frac{V_1 - V_4}{V_1 - V_3}$$

$$\text{Clearance Ratio} = \frac{\text{Clearance Volume}}{\text{Swept Volume}} = \frac{V_c}{V_s} = k \; (4\% - 10\ \%)$$

Reciprocating Compressor – Volumetric Efficiency

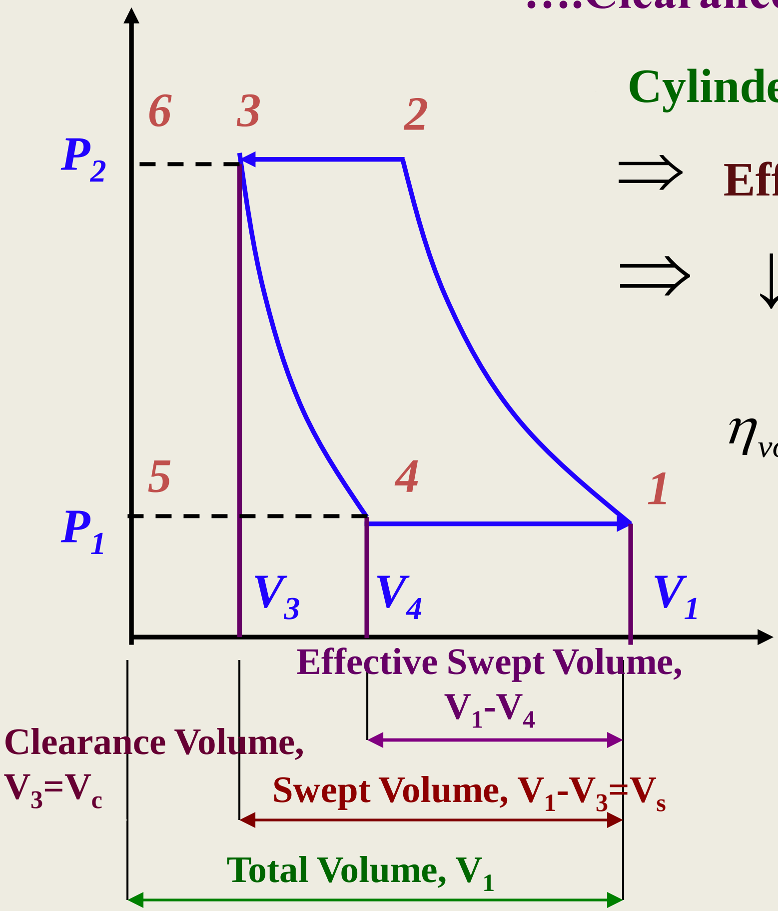
$\uparrow$ Pr. Ratio $\Rightarrow \uparrow$ Effect of Clearance Volume

….Clearance air expansion through greater volume before intake

Cylinder bore and stroke is fixed.

$\Rightarrow$ Effective Swept Volume (V1 – V4) $\downarrow$ with $\uparrow$ Pr. Ratio

$\Rightarrow$ $\downarrow$ Volumetric Efficiency



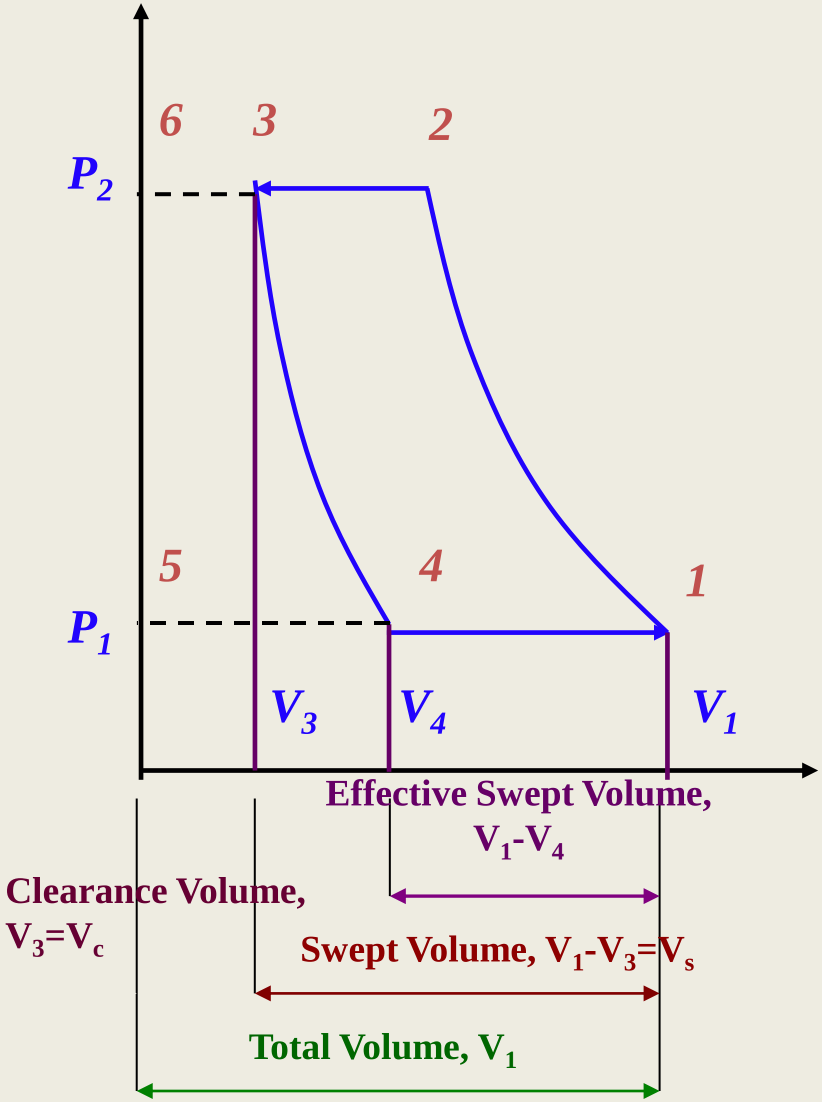
$$\eta_{vol} = \frac{V_1 - V_4}{V_1 - V_3}$$

$$= \frac{(V_1 - V_3) + (V_3 - V_4)}{(V_1 - V_3)} = 1 + \frac{V_3}{(V_1 - V_3)} - \frac{V_4}{(V_1 - V_3)}$$

$$= 1 + \frac{V_3}{(V_1 - V_3)} - \frac{V_4}{(V_1 - V_3)} \times \frac{V_3}{V_3}$$

$$= 1 + \frac{V_3}{(V_1 - V_3)} - \frac{V_3}{(V_1 - V_3)} \times \frac{V_4}{V_3}$$

Reciprocating Compressor – Volumetric Efficiency



$$\eta_{vol} = 1 + \frac{V_3}{(V_1 - V_3)} - \frac{V_3}{(V_1 - V_3)} \times \frac{V_4}{V_3}$$

$$\eta_{vol} = 1 + k - k\left(\frac{V_4}{V_3}\right)$$

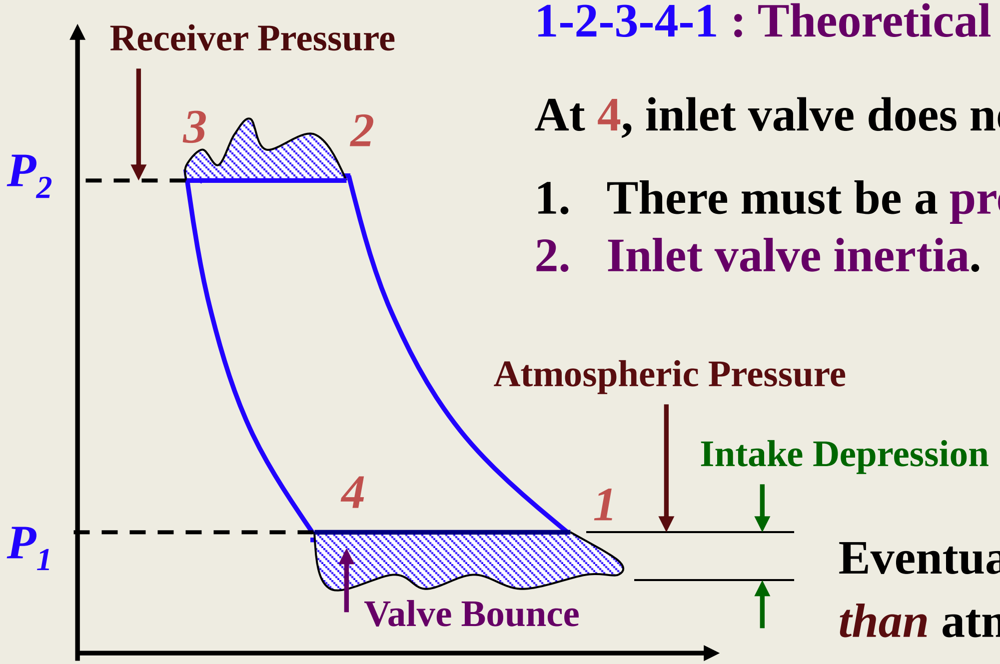
$$\eta_{vol} = 1 + k - k\left(\frac{P_3}{P_4}\right)^{1/n}$$

$$\eta_{vol} = 1 + k - k\left(\frac{V_1}{V_2}\right)$$

Factors which decrease Volumetric Efficiency

1. Very high speed.
2. Leakage past the piston
3. Large clearance volume
4. Obstruction at inlet valves
5. Heating of air by contact with hot cylinder walls
6. Inertia effect of air in suction pipe.

Reciprocating Compressor – Actual *P-V* Diagram



1-2-3-4-1 : Theoretical *P-V* Diagram.

At 4, inlet valve does not open because:

1. **There must be a pressure difference across the valve to open.**
2. **Inlet valve inertia.**

Pr. Drop continues till sufficient level for valve to force its seat.

Some *valve bounce* is set (wavy line).

Eventually, the pressure sets down at a level *lower than* atmospheric pressure. This negative pressure difference is known as *Intake Depression.*

Similar situation appears at 2, i.e. at the start of the delivery.

Pressure rise, followed by valve bounce and then pressure settles at a level *higher than* the delivery pressure level.

Air delivery to a tank / receiver, hence, generally known as *Receiver Pressure*.

Reciprocating Compressor – F.A.D.

Free Air Delivery (F.A.D.) : **If the volume of the air compressor is reduced to atmospheric temperature and pressure, this volume of air is called FAD (m^3/min)**

Delivered mass of air = intake mass of air

$$\frac{P_t V_t}{T_t} = \frac{P_1 \left(V_1 - V_4\right)}{T_1} = \frac{P_2 \left(V_2 - V_3\right)}{T_2}$$

If clearance volume is neglected

$$\frac{P_t V_t}{T_t} = \frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

Where

$$P_t = 101.325 KN / m^2$$

$$T_t = 20^0 C = 293 K$$

Reciprocating Compressor – Multistage

High Pressure required by Single – Stage :

$\Rightarrow$

1. **Requires heavy working parts.**
2. **Has to accommodate high pressure ratios.**
3. **Increased balancing problems.**
4. **High Torque fluctuations.**
5. **Requires heavy Flywheel installations.**

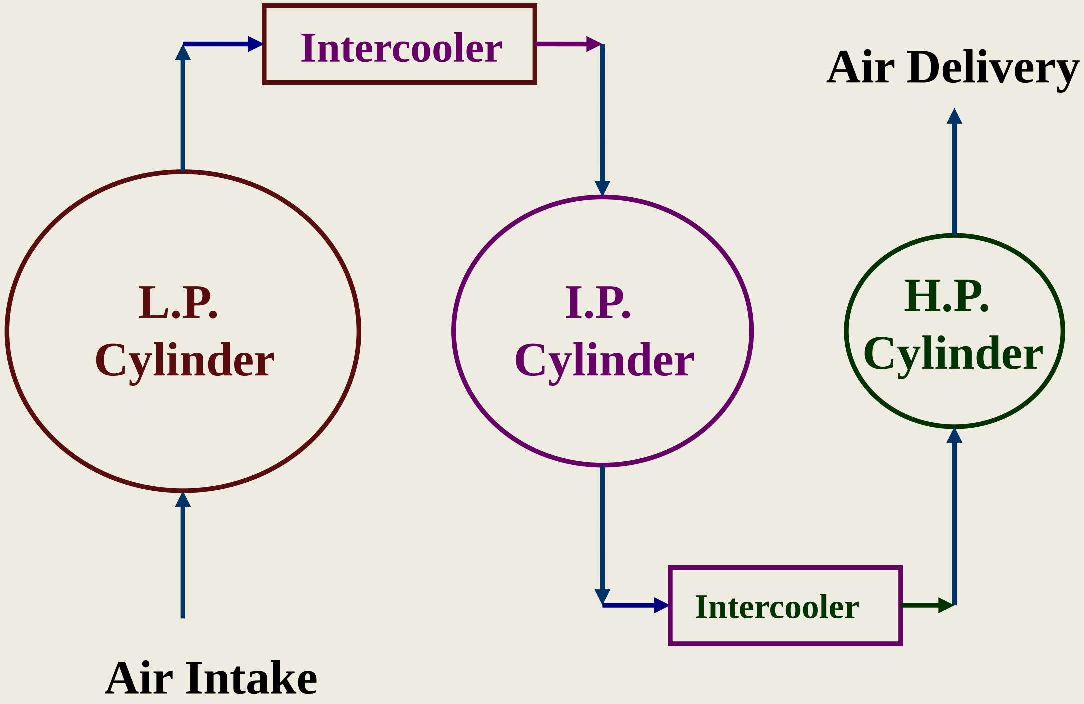
This demands for MULTI – STAGING…!!

Why multistage compressor?

- High temp rise leads into limitation for the maximum achievable pressure rise.
- Discharge temperature shall not exceed 150ºC and should not exceed 135^{0}C for hydrogen rich services
- A multistage compressor compresses air to the required pressure in multiple stages.
- Intercoolers are used in between each stage to removes heat and decrease the temperature of gas so that gas could be compressed to higher pressure without much rise in temperature

Reciprocating Compressor – Multistage

Series arrangement of cylinders, in which the compressed air from earlier cylinder (i.e. *discharge*) becomes the intake air for the next cylinder (i.e. *inlet*).



L.P. = Low Pressure

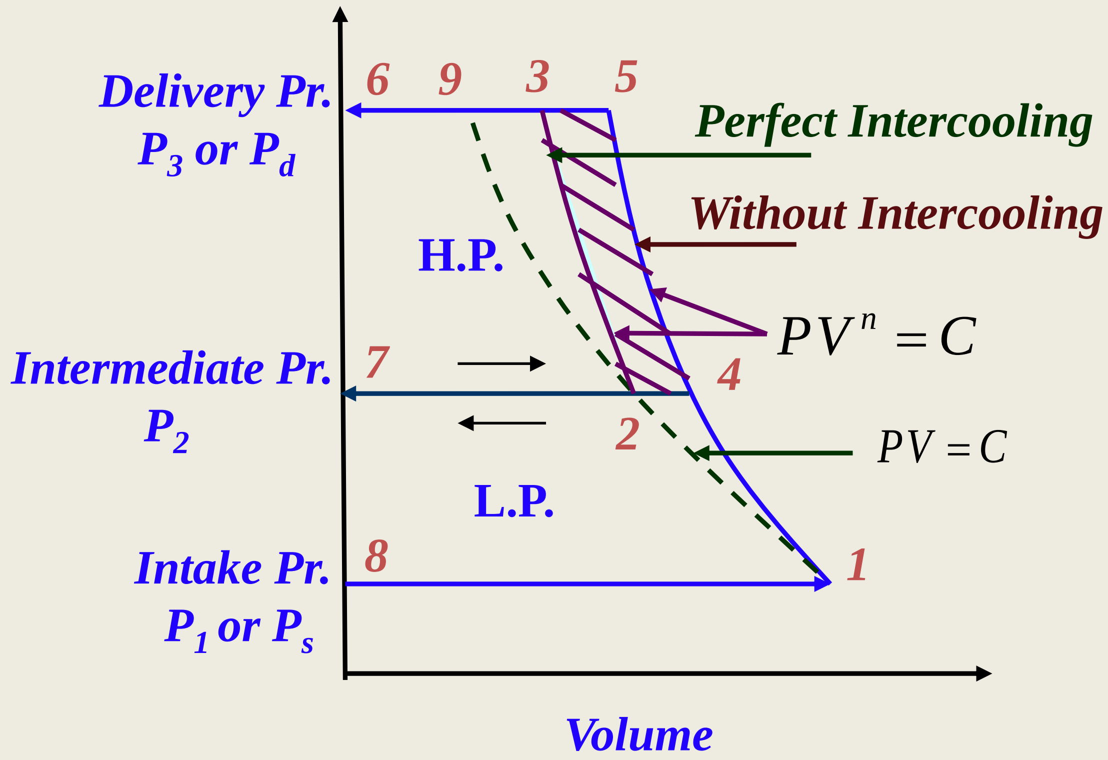
I.P. = Intermediate Pressure

H.P. = High Pressure

***Intercooler* :**

Compressed air is *cooled* between cylinders.

Reciprocating Compressor – Multistage



Overall Pr. Range : $P_1 – P_3$

Single – stage cycle : 8-1-5-6

Without Intercooling :

L.P. : 8-1-4-7

H.P. : 7-4-5-6

With Intercooling :

L.P. : 8-1-4-7

H.P. : 7-2-3-6

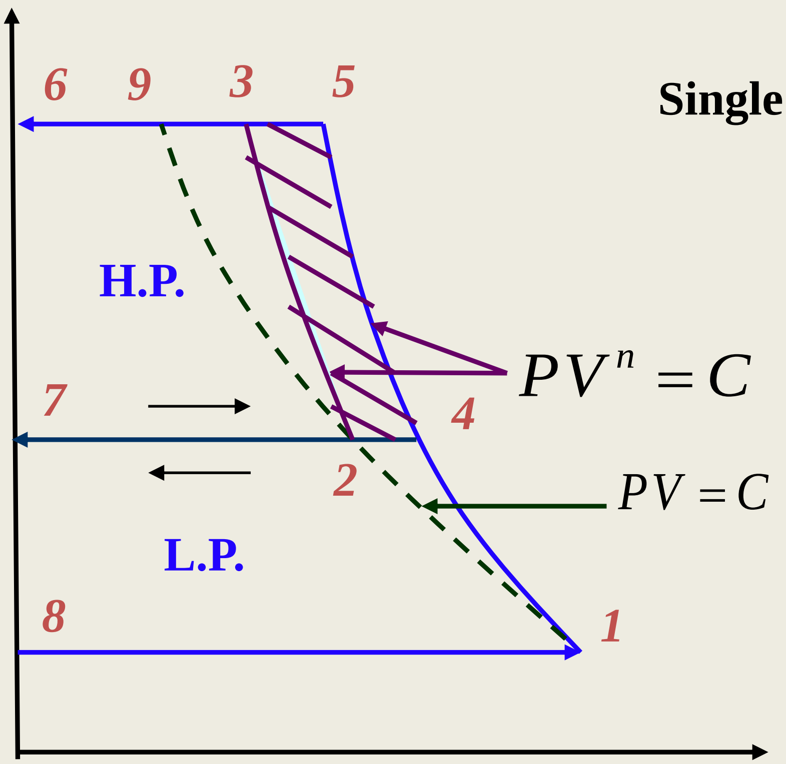
Perfect Intercooling **: After initial compression in L.P. cylinder, air is cooled in the Intercooler to its original temperature, before entering H.P. cylinder i.e. $T_2 = T_1$ OR**

Points 1 and 2 are on SAME Isothermal line.

Reciprocating Compressor – Multistage

Ideal Conditions for Multi – Stage Compressors :

A. Single – Stage Compressor :



Single – stage cycle : 8-1-5-6

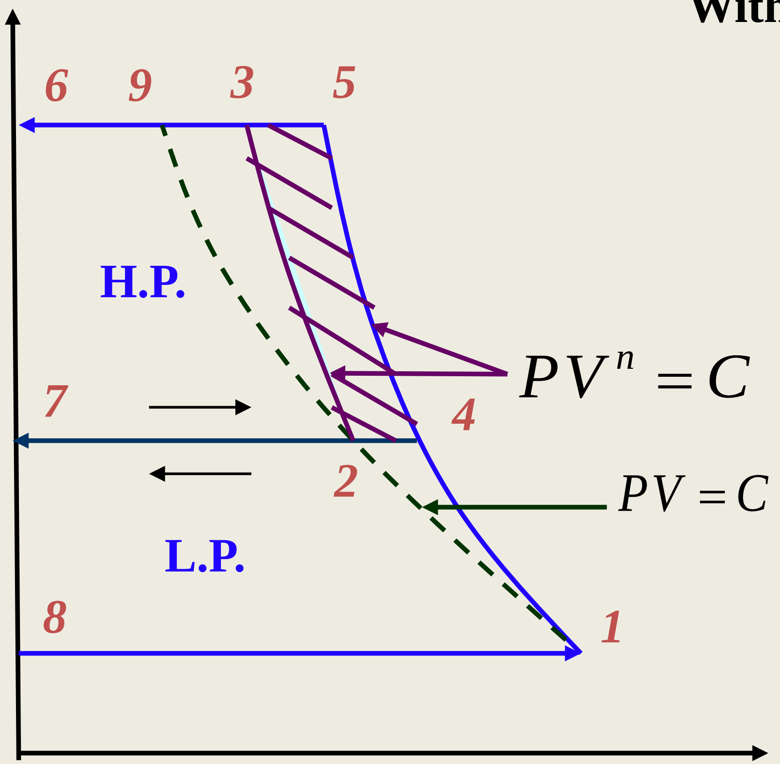
$$W = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_5}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

Delivery Temperature,

$$T_5 = T_1 \left(\frac{P_5}{P_1} \right)^{\frac{n-1}{n}}$$

Reciprocating Compressor – Multistage

B. <u>Two – Stage Compressor</u> *(Without Intercooling)* :



Without Intercooling :

L.P. : 8-1-4-7

H.P. : 7-4-5-6

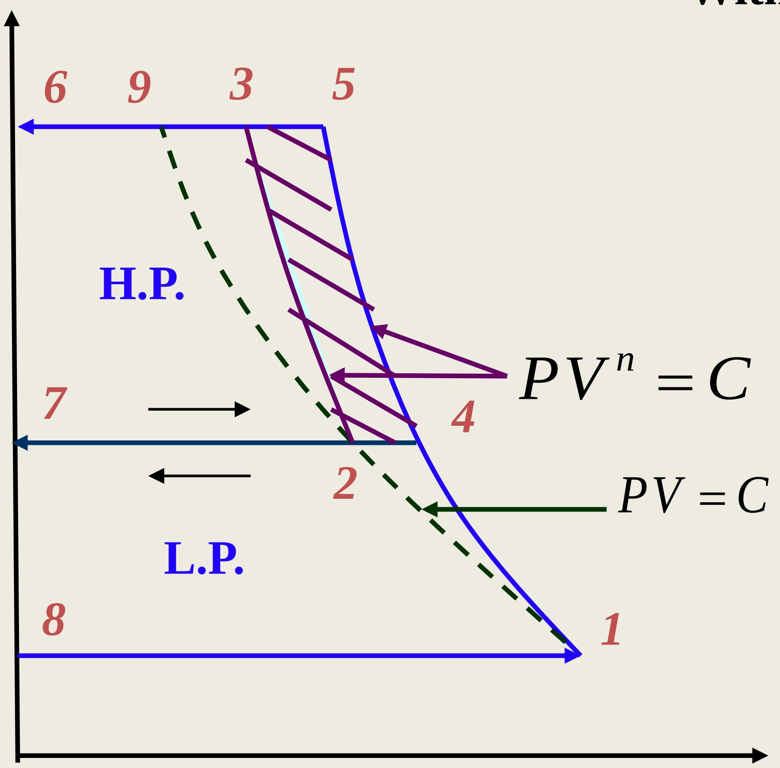
$$W = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_4}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] + \frac{n}{n-1} P_4 V_4 \left[\left(\frac{P_5}{P_4} \right)^{\frac{n-1}{n}} - 1 \right]$$

Without Intercooling $\Longrightarrow$ **This is SAME as that of Work done in Single – Stage.**

Delivery Temperature also remains SAME.

Reciprocating Compressor – Multistage

C. Two – Stage Compressor ***(With Perfect Intercooling)*** **:**



With Intercooling :

L.P. : 8-1-4-7-8

H.P. : 7-2-3-6-7

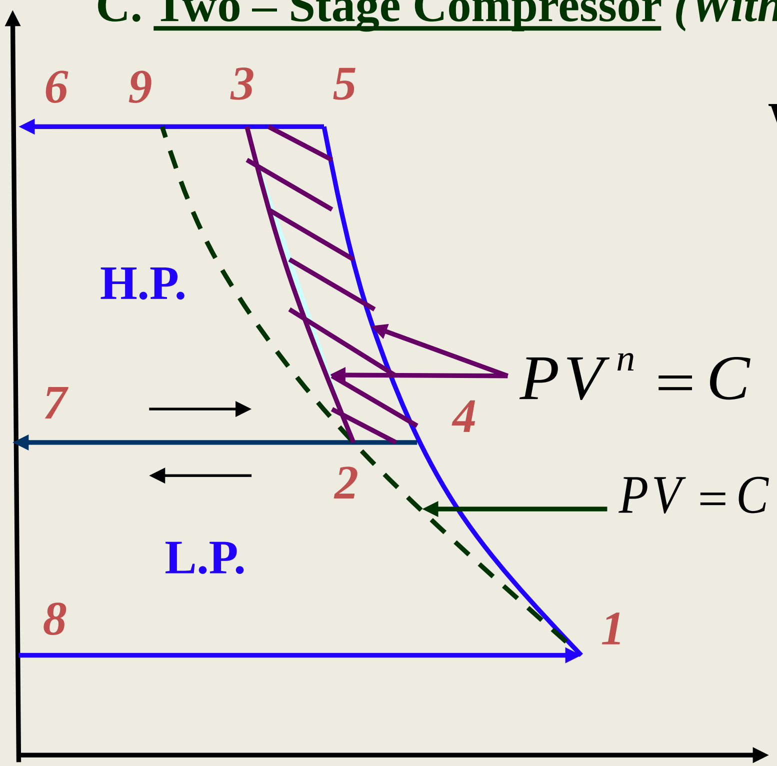
$$W = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_4}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] + \frac{n}{n-1} P_2 V_2 \left[\left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} - 1 \right]$$

Delivery Temperature,

$$T_3 = T_2 \left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} = T_1 \left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}}, \quad as\ T_2 = T_1$$

Reciprocating Compressor – Multistage

C. <u>Two – Stage Compressor</u> *(With Perfect Intercooling)* :



With Intercooling :

L.P. : 8-1-4-7-8

H.P. : 7-2-3-6-7

Now, $T_2 = T_1$

$P_2V_2 = P_1V_1$

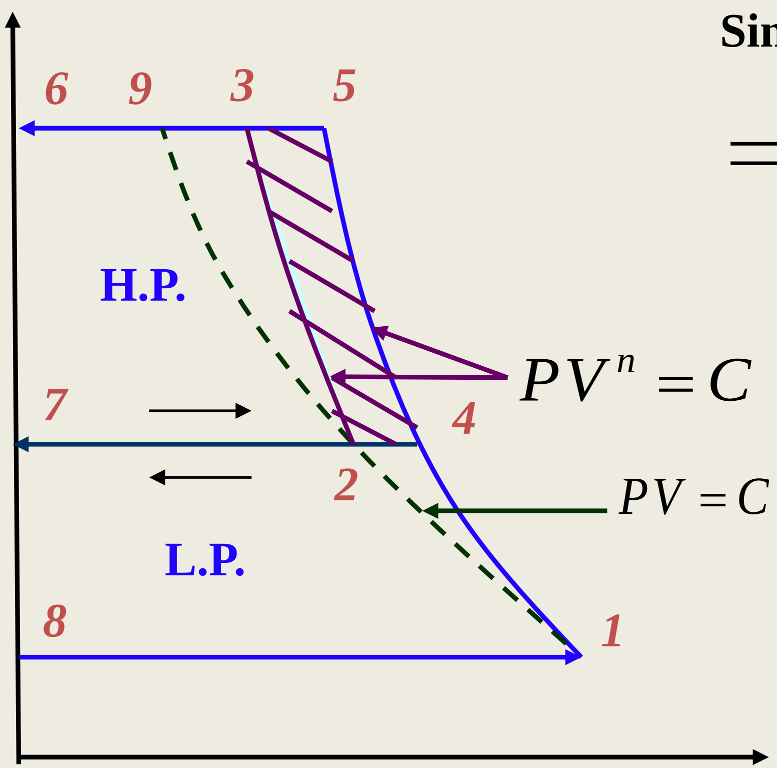
Also $P_4 = P_2$

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

Shaded Area 2-4-5-3-2 : Work Saving due to Intercooler…!!

Reciprocating Compressor – Multistage

Condition for Min. Work :



Since P_1 and P_3 are fixed

$\Longrightarrow$ **There is an *Optimum* P_2 for which Area 2-4-5-3-2 is maximum,**

i.e. Work is minimum…!!

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

For min. Work,

$$\frac{dW}{dP_2} = \frac{d\left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2} \right)^{\frac{n-1}{n}} \right]}{dP_2} = 0$$

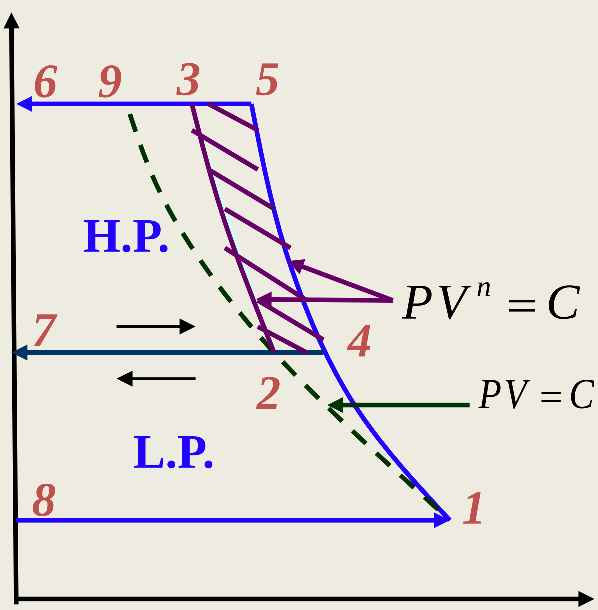
Reciprocating Compressor – Multistage

Condition for Min. Work :

$$\frac{dW}{dP_2} = \frac{d\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}}\right]}{dP_2} = 0$$

$$let\ \frac{n-1}{n} = x$$

$$\frac{1}{(P_1)^x} \bullet x\,(P_2)^{x-1} \underset{\frac{n-1}{n}}{+} (P_3)^x \bullet \left[-x\,(P_2)^{-x-1}\right] = 0$$



$$\frac{(P_2)^{x-1}}{(P_2)^{-x-1}} = (P_1\,P_3)^x$$

$$(P_2)^2 = (P_1\,P_3)$$

$$\boxed{P_2 = \sqrt{P_1\,P_3} \quad OR \quad \frac{P_2}{P_1} = \frac{P_3}{P_2}}$$

Reciprocating Compressor – Multistage

P_2 obtained with this condition (Pr. Ratio per stage is equal) is the Ideal Intermediate Pr. Which, with <u>Perfect Intercooling</u>, gives Minimum Work, W_{min}.

$\Longrightarrow$ **Equal Work per cylinder…!!**

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

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

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

Reciprocating Compressor – Performance

Isothermal work done / cycle = Area of *P* – *V* Diagram

$$= P_1V_1 \log_e (P_2/P_1)$$

$$= 2.3\, P_1V_1 \log (P_2/P_1)$$

Isothermal Power $= \text{Isothermal work done / cycle} \times \dfrac{N}{60 \times 1000}\ kW$

Indicated work done = **Work done during polytropic compression**

$$= \frac{n}{n-1} \times P_1\, V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

Indicated Power $= \text{Indicated work done} \times \dfrac{N}{60 \times 1000}\ kW$

Reciprocating Compressor – Performance

Isothermal/Compressor Efficiency $$\eta_c = \frac{Isothermal\ work\ done}{Indicated\ work\ done} = \frac{Isothermal\ power}{Indicated\ power}$$

Overall Isothermal Efficiency $$\eta_o = \frac{Isothermal\ power}{Shaft\ power\ or\ B.P.of\ motor}$$

Mechanical Efficiency $$\eta_m = \frac{Indicated\ power}{Shaft\ power\ or\ B.P.of\ motor}$$

Isentropic/Adiabatic Efficiency $$\eta_i = \frac{Isentropic\ power}{Shaft\ power\ or\ B.P.of\ motor}$$

(for isentropic efficiency replace n with γ in overall isothermal efficiency.)

Volumetric Efficiency $$\eta_{v(amb)} = \frac{Free\ air\ delivered\ per\ stroke}{Swept\ volume\ of\ piston}$$

$$= \frac{P_1 T_a}{P_a T_1}\left[1 + K - K\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}\right]$$

$$= \frac{P_1 T_a}{P_a T_1}\left[1 + K - K\left(\frac{V_2}{V_1}\right)\right]$$

(When the ambient and suction conditions are same, then $P_a = P_1\ and\ T_a = T_1$)

Reciprocating Compressor – Efficiency

How to Increase Isothermal Efficiency ?

A. Spray Injection : Injects water into the compressor cylinder towards the end of compression stroke.

Object is to cool the air.

Demerits : 1. Requires *special gear* for injection.

2. Injected water interferes with the *cylinder lubrication*.

3. Damage to *cylinder walls* and *valves*.

4. Water must be separated before delivery of air.

B. Water Jacketing : Circulating water around the cylinder to help for cooling the air during compression.

Reciprocating Compressor – Efficiency

How to Increase Isothermal Efficiency ?

C. **Inter – Cooling : For high speed and high Pr. Ratio compressors.**

Compressed air from earlier stage is cooled to its original temperature before passing it to the next stage.

D. **External Fins : For small capacity compressors, fins on external surfaces are useful.**

E. **Cylinder Proportions : Short stroke and large bore provides much greater surface for cooling.**

Cylinder head surface is far more effective than barrel surface.

Reciprocating Compressor – Efficiency

Clearance Volume : Consists of *two* spaces.

1. Space between cylinder end & the piston to allow for wear.

2. Space for reception of valves.

High – class H.P. compressors : Clearance Vol. = 3 % of Swept Vol.

: Lead (Pb) fuse wire used to measure the gap between cylinder end and piston.

Low – grade L.P. compressors : Clearance Vol. = 6 % of Swept Vol.

: Flattened ball of putty used to measure the gap between cylinder end and piston.

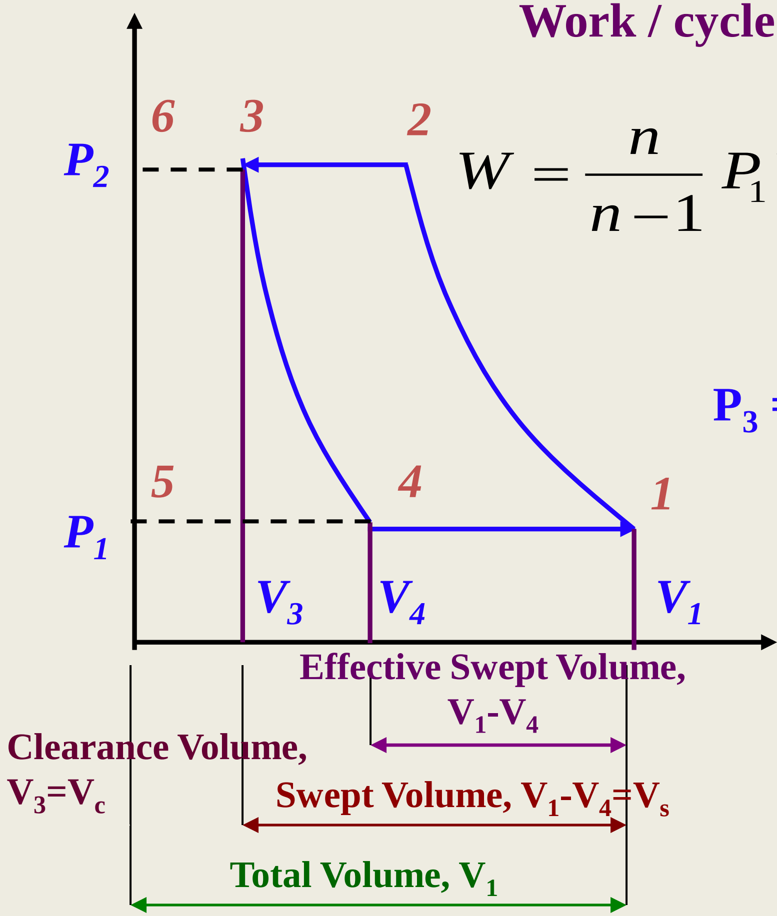
Effect of Clearance Vol. :

Vol. taken in per stroke < Swept Vol. $\Longrightarrow$ $\uparrow$ **Size of compressor**

$\uparrow$ **Power to drive compressor.**

Reciprocating Compressor – Work Done

Assumption : Compression and Expansion follow same Law.



Work / cycle = Area 1-2-3-4-1

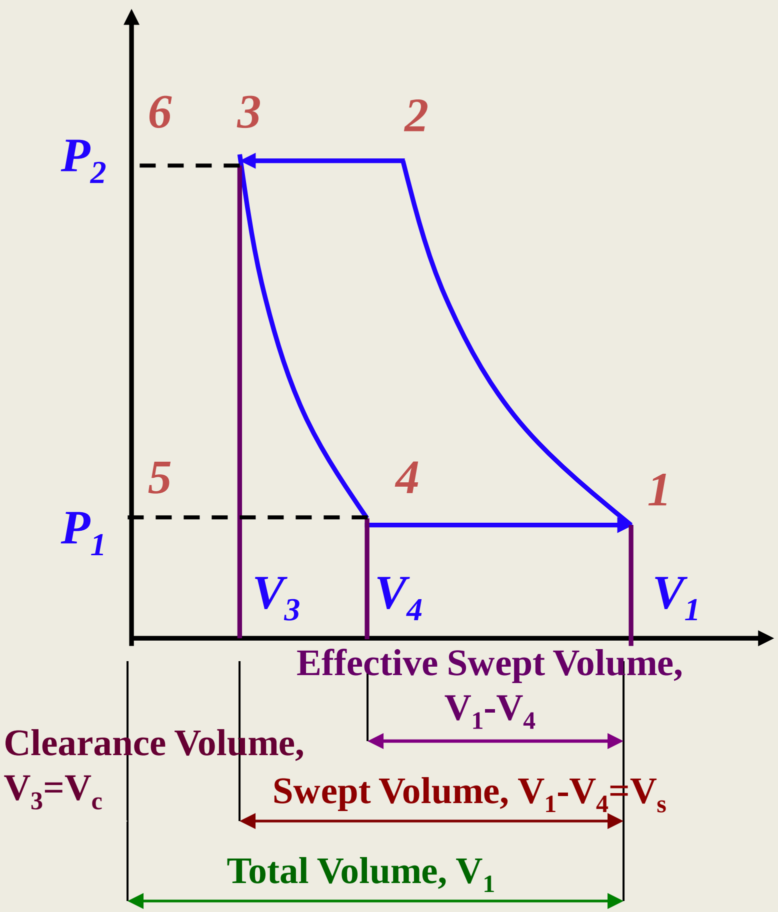
$$W = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] - \frac{n}{n-1} P_4 V_4 \left[\left(\frac{P_3}{P_4} \right)^{\frac{n-1}{n}} - 1 \right]$$

$P_3 = P_2$ and $P_4 = P_1$

$$W = \frac{n}{n-1} P_1 (V_1 - V_4) \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

$$= \frac{n}{n-1} P_1 V_a \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

Reciprocating Compressor – Work Done



$$W = \frac{n}{n-1} m_1 R T_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

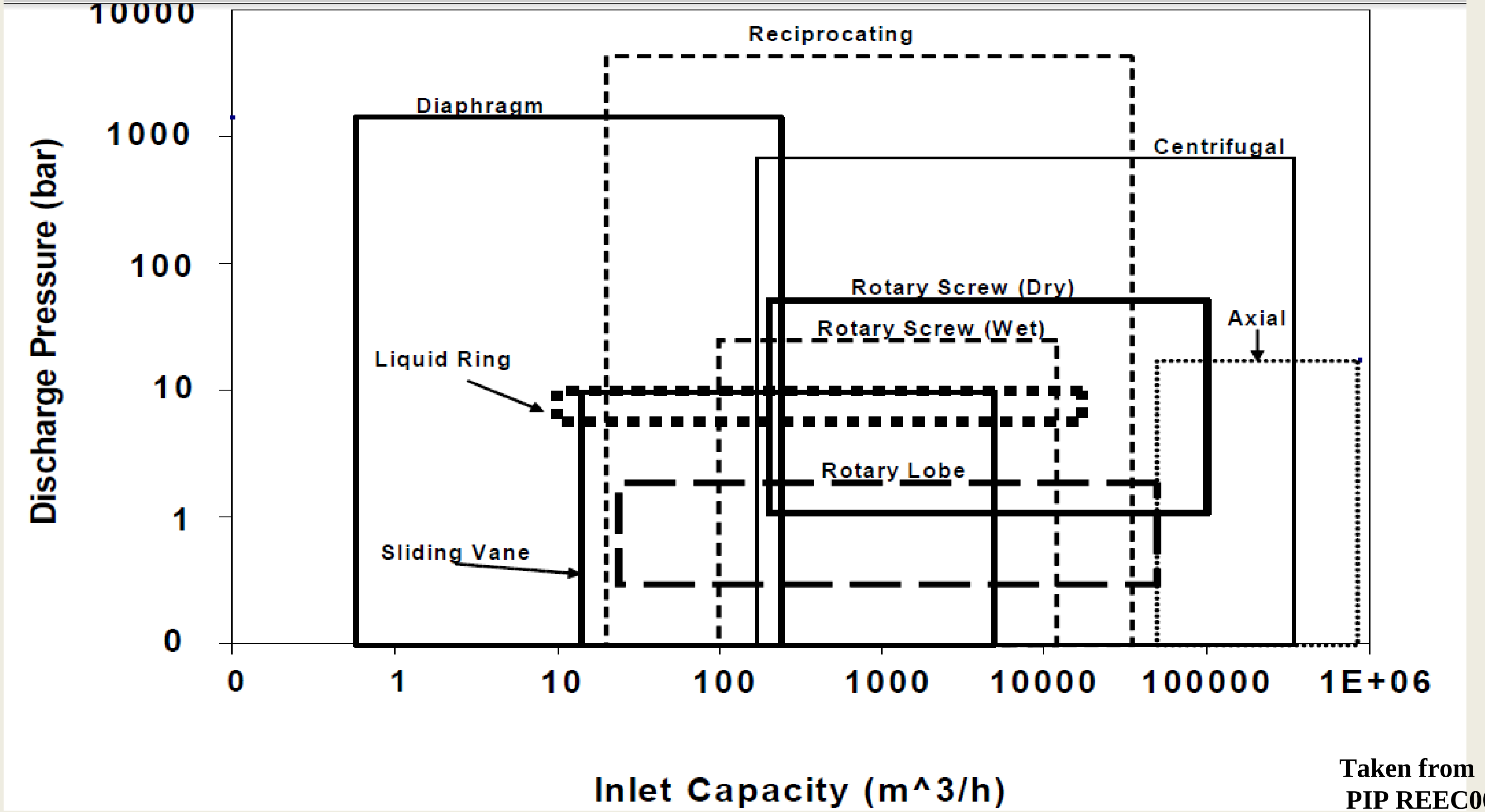
m_1 is the actual mass of air delivered.

Work done / kg of air delivered :

$$W = \frac{n}{n-1} R T_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

How to select a particular type of compressor ?

Graph showing operating regions of various compressors



Taken from
PIP REEC001
Compressor Selection
Guidelines

Table showing operating conditions of various compressors

Table 1b. Summary of Typical Operating Characteristics of Compressors (US Units)

	Inlet Capacity (acfm)	Maximum Discharge Pressure (psig)	Efficiency (%)	Operating Speed (rpm)	Maximum Power (HP)	Application
Dynamic Compressors						
Centrifugal	100 - 200,000	10,000	70 – 87	1,800 - 50,000	50,000+	Process gas & air
Axial	30,000 - 500,000	250	87 - 90+	1,500 - 10,000	100,000	Mainly air
Positive Displacement Compressors						
Reciprocating (Piston)	10 - 20,000	60,000	80 – 95	200 - 900	20,000	Air & process gas
Diaphragm	0.5 – 150	20,000	60 – 70	300 - 500	2,000	Corrosive & hazardous process gas
Rotary Screw (Wet)	50 - 7,000	350	65 – 70	1,500 - 3,600	2000	Air, refrigeration & process gas
Rotary Screw (Dry)	120 – 58,000	15 – 700	55 – 70	1,000 - 20,000	8,000	Air & dirty process gas
Rotary Lobe	15 - 30,000	5 - 25	55 – 65	300 - 4,000	500	Pneumatic conveying, process gas & vacuum
Sliding Vane	10 - 3,000	150	40 – 70	400 - 1,800	450	Vacuum service & process gas
Liquid Ring	5 - 10,000	80 - 150	25 – 50	200 - 3,600	400	Vacuum service & corrosive process gas

Taken from
PIP REEC001
Compressor Selection Guidelines

Advantages and Disadvantages of Dynamic compressors

	Advantages	Disadvantages
Dynamic Compressors		
Centrifugal	•Wide operating range •High reliability •Low Maintenance	•Instability at reduced flow •Sensitive to gas composition change
Axial	•High Capacity for given size •High efficiency •Heavy duty •Low maintenance	•Low Compression ratios •Limited turndown

Advantages and Disadvantages of Positive displacement compressors

	Advantages	Disadvantages
Positive displacement compressor		
Reciprocating	•Wide pressure ratios •High efficiency	•Heavy foundation required •Flow pulsation •High maintenance
Diaphragm	•Very high pressure •Low flow •No moving seal	•Limited capacity range •Periodic replacement of diaphragm
Screw	•Wide application •High efficiency •High pressure ratio	•Expensive •Unsuitable for corrosive or dirty gases

Thank You