THERMAL ENGINEERING-II

Transcript of lectures I have given at Govt. polytechnic, Boudh. Keeping in view of the Pandemic COVID 19 the classes have to be shut down. In a short time I have prepared this but it will be interesting, as if two way of communication between you and me. All other chapters will be followed by.

LECTURE NOTES

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Syllabus

Chapter 1

Performance of I.C Engine

i. Define mechanical efficiency, indicated thermal efficiency, relative efficiency, brake thermal efficiency, overall efficiency, mean effective pressure & specific fuel consumption
ii. Define air fuel ratio & calorific value of fuel
iii. Work out problems to determine efficiencies & specific fuel consumption

Chapter 2

Air compressor

i. Explain functions of compressor & industrial use of compressed air
ii. Classify air compressor and principle of operation
iii. Describe the parts and working principle of reciprocating air compressor
iv. Explain terminology of reciprocating air compressor such as bore, stroke, pressure ratio, free air delivery & volumetric efficiency
v. Derive the work done of single stage & two stage compressor with and without clearance
vi. Solve simple problems. (without clearance only)

Chapter 3

Properties of Steam

i. Differentiate between gas & vapour
ii. Formation of steam
iii. Representation on P-V, T-S, H-S diagram
iv. Definition & properties of steam
v. Use of steam table & mollier chart for finding unknown properties
vi. Non flow and flow process of vapour
vii. P-V, T-S, H-S diagram

viii. Determine the change in properties & solve simple numericals

Chapter 4

Steam generator

i. Classification and types of boiler
ii. Important terms of boiler
iii. Comparison between fire tube & water tube boiler
iv. Description and working of common boilers (Cochran, Lancashire, Babcock & Wilcox boiler)
v. Boiler draught (Forced, Induced & balanced)
vi. Boiler mountings and accessories

Chapter 5

Steam power cycle

i. Carnot cycle with vapour
ii. Derive work and efficiency of the cycle
iii. Rankine cycle
    - Representation in P-V, T-S & H-S diagram
    - Derive work & efficiency
    - Effect of various end conditions in Rankine cycle
    - Reheat cycle & Regenerative cycle
iv. Solve simple numerical on Carnot vapour cycle & Rankine cycle

Chapter 6

Heat transfer

i. Modes of Heat transfer (Conduction, convection, Radiation)
ii. Fourier law of heat conduction and thermal conductivity
iii. Newton’s law of cooling
iv. Radiation heat transfer (Stefan Boltzman law, Kirchoff law only statement)
v. Black body radiation, definition of emmisivity, absorptivity and transmissivity

Air Compressor

Functions of compressor

- Compressor is a thermodynamic device which is used to increase the pressure of air from atmospheric pressure (Suction pressure) to high pressure (delivery pressure) by consumption of external work input.

- Since Pressure is directly proportional to temperature $P \propto T$ every rise in pressure is associated with rise in temperature which is an undesirable effect. So every compression process should be associated with cooling.

USES OF COMPRESSED AIR

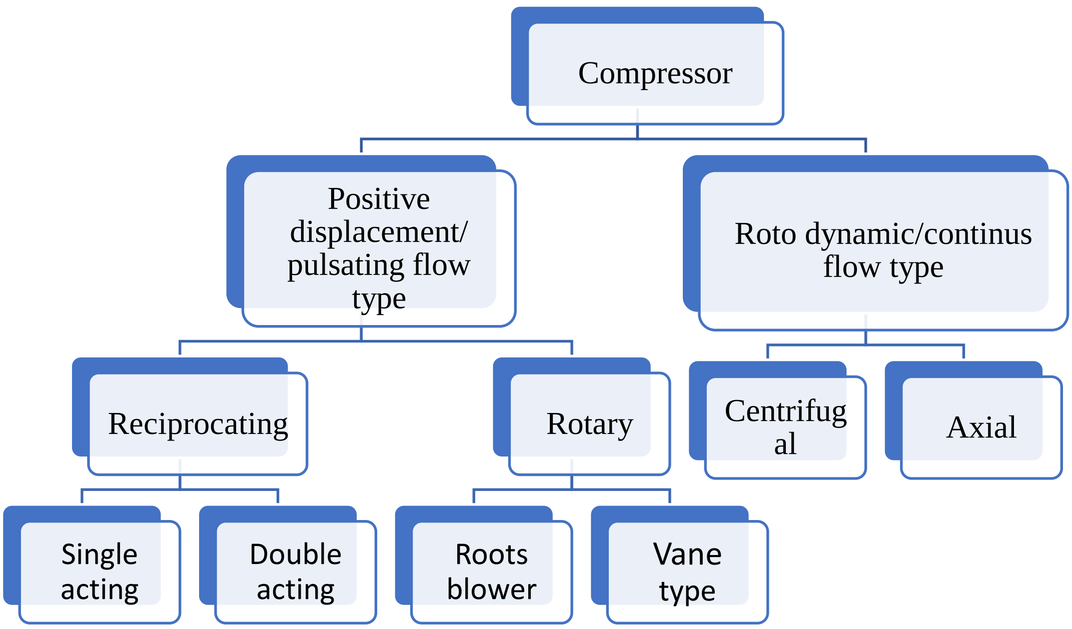
Domestic use

- Cleaning purpose
- Inflating automobile tyres
- operating air brakes
- Spray painting

Industrial use

- Driving pneumatic drill
- Blast furnace
- supercharging of IC engines
- process industries
- Operating lifts, hoists and crains

CLASSIFICATION OF AIR COMPRESSOR



Principle of operation

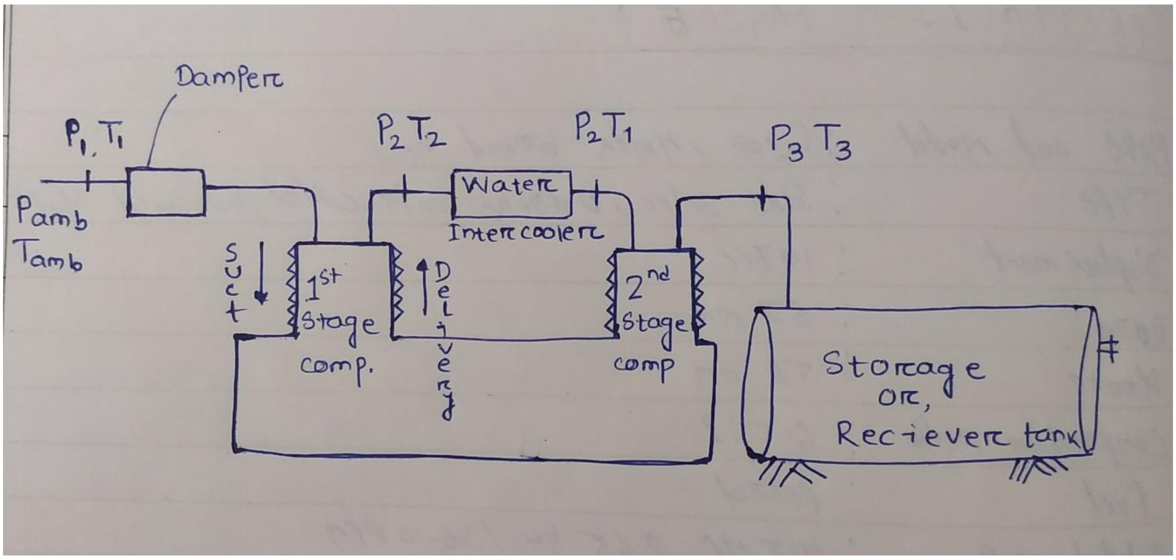


Figure 1 line diagram of a two-stage compressor with intercooler

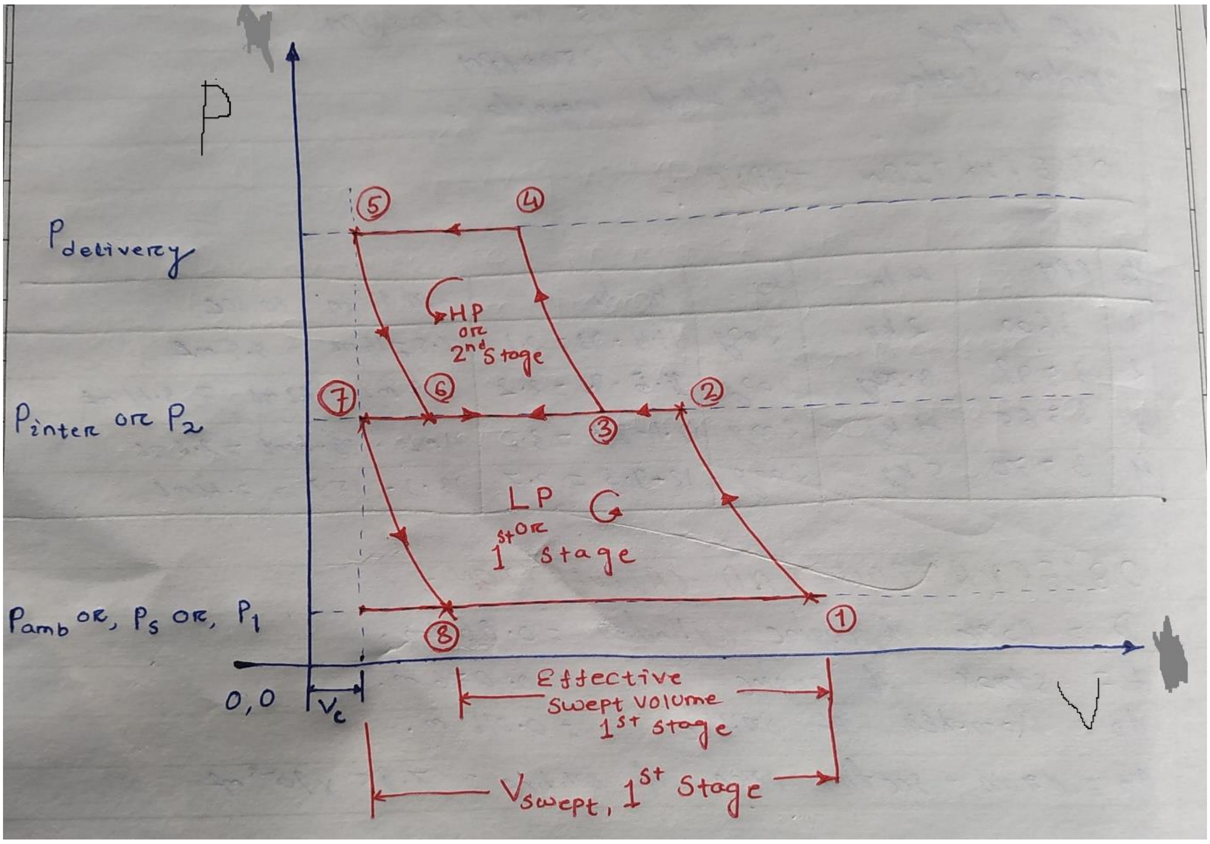


Figure 2Indicator diagram of a two stage reciprocating air compressor

- Atmospheric air at P_{amb}, T_{amb} or (P_1, T_1) is inducted into 1st stage compressor.
- It is inducted through an air filter and damper to admit clean and moisture free air into compressor
- Atmospheric air is compressed inside cylinder until delivery pressure of 1st stage compressor is attained
- Delivery pressure is set by a compression spring mounted over delivery valve.
- 1st stage compressor increases the pressure and temperature of air from P_1, T_1 to P_2, T_2 at this state air admits into 2nd stage compressor through intercooler. At the intercooler exit temperature of compressed air drops to again T_1 if it is a perfect intercooling. Necessarily intercooler is a heat exchanger and ideal thermodynamic process for an intercooler is constant pressure cooling.
- Name of the intercooler is justified as it is placed in between two compressors
- State of air incoming to 2nd stage compressor is P_2, T_1 and it compressed to the desired pressure P_3 in the consequence temperature is increased to T_3.
- The corresponding P-V (indicator diagram) for the thermodynamic process is shown as below

TERMINOLOGY OF RECIPROCATING AIR COMPRESSOR

- **Compression ratio (r):** It is defined as the ratio of volume of air before compression to the volume of air after compression.
- **Compressor capacity:** It is the quantity of air actually delivered by a compressor in m3/minute or m3/sec.
- **Free air Delivered (FAD): -** It is the volume of air delivered by compressor under the compressor intake conditions (i.e. local atmospheric temperature and pressure).
- **Swept Volume (V_s):** The volume displaced or swept by piston when it moves between top dead centre and bottom dead centre.

- **Clearance volume (V_C):** it is the difference between the total **volume** and the swept **volume**, basically the gap that remains between the piston head and the cylinder head when at top dead centre.

- **Volumetric efficiency (η_{vol}):** It is the ratio of actual volume of the FAD at standard atmospheric condition in one delivery stroke (Actual air intake) to the swept volume (theoretical air intake) by the piston during the stroke.

- **Isothermal efficiency(η_{iso}):** It is defined as the ratio of isothermal power (P_{iso}) (i.e. required input power at isothermal process) done to the indicated power (IP) or actual work done.

- **Mechanical efficiency(η_{mech}):** It is the ratio of indicated power (IP) to the shaft (Brake) Power (P_{shaft}).

- **Overall efficiency(η_o):** It is the ratio of isothermal power (P_{iso}) to the shaft (Brake) Power (P_{shaft}).

LAW OF COMPRESSION

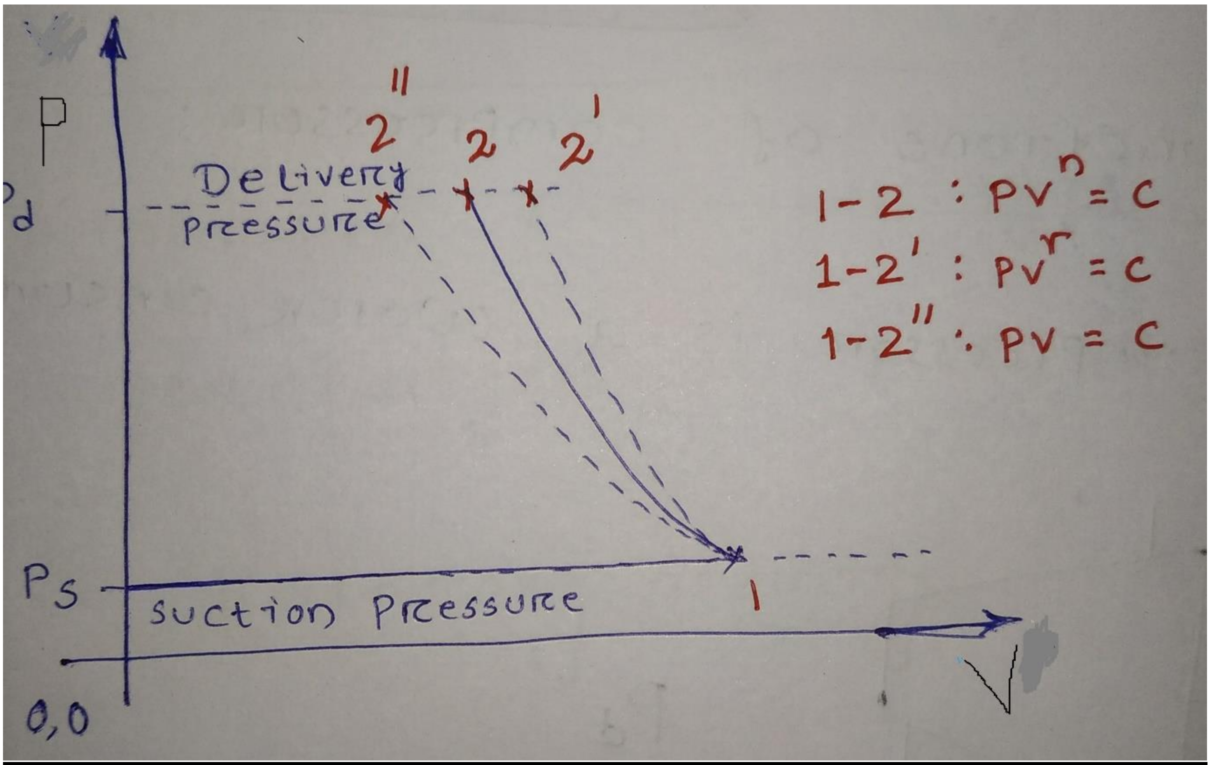


Figure 3 Law of compression comparison among Isothermal polytropic & adiabatic compression

- The cycle of operation of a reciprocating air-compressor is best shown on a pressure-volume (p-V) diagram.
- It is known as an indicator diagram for the compressor.
- The cycle comprises of three processes: An induction stroke, a compression stroke, a delivery stroke

- During the induction or, suction stroke Intake valve opens, while exhaust valve closed. Atmospheric air is drawn into the cylinder at constant pressure $P_1$and temperature T_1. Ideally, there is no heat loss to the surrounding from the air.

- During the compression stroke both intake and exhaust valves are closed. The air is compressed according to a polytropic law PV^n = constant. Its pressure is increased from P_1 ($P_{suction}$) to P_2. ($P_{delivery}$) The temperature is also increased from T1 to T2.

- During the delivery or discharge stroke the intake valve is closed while the exhaust valve opens. The compressed air is pushed out of the cylinder at constant pressure P_2 and temperature T2. There is no heat loss from the air to the surroundings.

- During compression, air inside compressor gets more heated than surrounding, the air will lose some heat. Thus neglecting the internal effect of friction the index is less than γ (i.e. <1.4), the adiabatic index.

- If $n= \gamma=1.4$, area under curve is biggest, i.e. reversible adiabatic or entropy constant.

- Since work must be put into an air compressor to run it, every effort is made to reduce this amount of work input. It is observed that if compression is along isothermal, work done is less (though in practical it is not possible). Isothermal is attempted by cooling the compressor either by adding cooling fan or, incorporating intercooler and aftercooler

WORK DONE ON COMPRESSOR

For ease in remembering and deriving mathematical expression to calculate work need to be done on compressor a simple hierarchy I am presenting students, they only need to derive

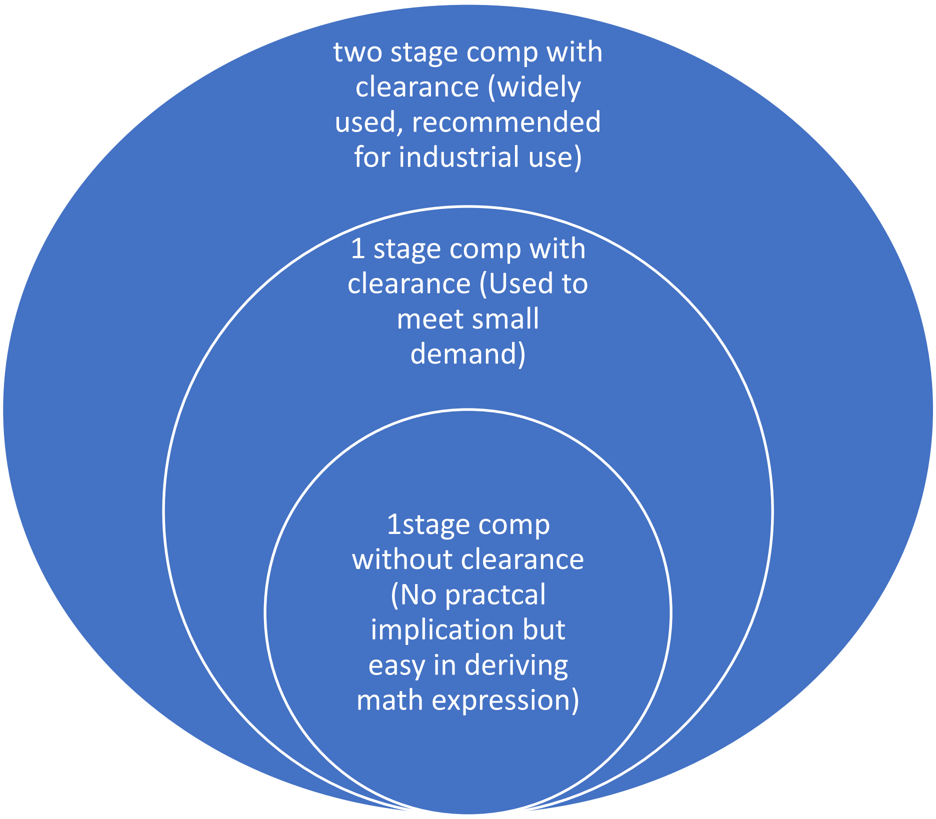


Figure 4 Hierarchy of work consumption for various type of compressors

WORK CONSUMPTION BY SINGLE STAGE RAC NO CLEARANCE

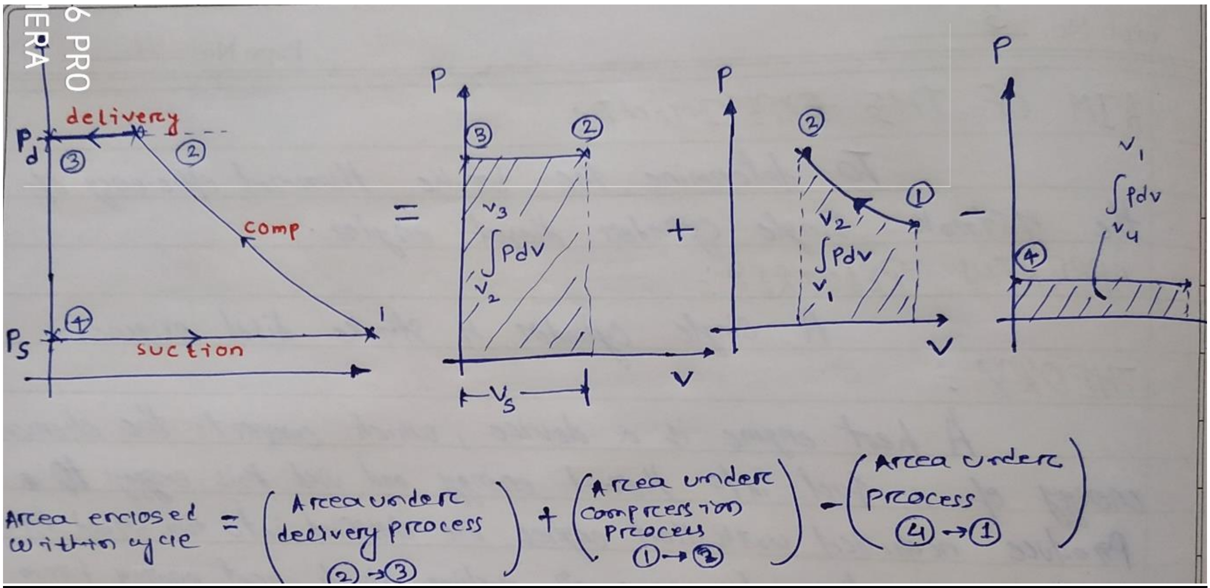


Figure 5 Work consumption by single stage compressor having no clearance volume

$$\frac{W}{cycle} = [Pd(V2 - V3)] + \left[\frac{P2V2 - P1V1}{n - 1}\right] - [Ps(V1 - V4)]$$

$$\frac{W}{cycle} = PdV2 - PdV3 + \frac{P2V2 - P1V1}{n - 1} - PsV1 + PsV4$$

$$\frac{W}{cycle} = \frac{PdV2(n - 1)}{n - 1} + \frac{P2V2 - P1V1}{n - 1} - \frac{PsV1(n - 1)}{n - 1}$$

Since V3 = 0 & V4 = 0

$$\frac{W}{cycle} = \frac{nPdV2 - PdV2 + P2V2 - P1V1 - nPsV1 + PsV1}{n - 1}$$

Since PdV2 = P2V2 & P1V1 = Ps=V1

$$\frac{W}{cycle} = \frac{nPdV2 - nPsV1}{n - 1}$$

$$\frac{W}{cycle} = n\frac{PdV2 - PsV1}{n - 1} \quad (\frac{kJ}{Cycle})$$

$$\frac{W}{cycle} = \frac{n}{n - 1}[PdV2 - PsV1] \quad (\frac{kJ}{Cycle})$$

Power requirement (from indicator diagram) or, ideal power requirement for the compressor is $IP = \frac{n}{n-1}[PdV2 - PsV1] \times N \frac{rev}{min} \times \frac{1min}{60\ sec}\ \ (kW)$

- But actual power consumed by air compressor can be calculated by considering η_{mech} (mechanical efficiency) and η_{elect} (Electrical efficiency) which can be very well interpreted from the figure below

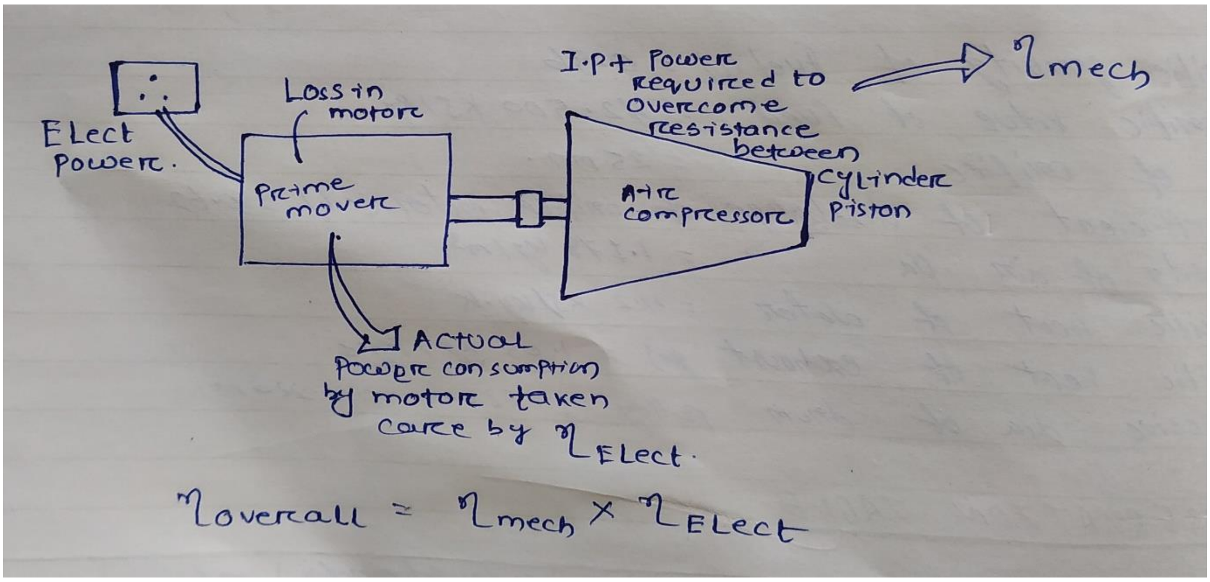


Figure 6 representation of electrical loss & mechanical loss

$$\frac{W}{cycle} = \frac{n}{n-1}[P2V2 - P1V1](\frac{kJ}{cycle})$$

$$= \frac{n}{n-1}[\dot{m}\frac{kg}{cycle}RT2 - \dot{m}RT1]\ (\frac{kJ}{cycle})$$

$$= \frac{n}{n-1}\dot{m}\frac{kg}{cycle}RT1[\frac{T2}{T1} - 1]\ (\frac{kJ}{cycle})$$

For thermodynamic compression process 1-2 we can use any of the following thermodynamic relations

$PV^n = C$ or, $TV^{n-1} = C$ or, $TP^{\frac{1-n}{n}} = C$

$or, T1P1^{\frac{1-n}{n}} = T2P2^{\frac{1-n}{n}}$

Or, $\frac{P1}{P2}^{\frac{1-n}{n}} = \frac{T2}{T1}$

Putting this relation into expression of work consumed by a compressor a more usable format for expression can be found out. But it is up to your convenient to use any of the expression according to need

$$\frac{W}{cycle} = \frac{n}{n-1} m \frac{kg}{cycle} RT1[\left(\frac{P2}{P1}\right)^{\frac{n-1}{n}} - 1] \frac{kJ}{Cycle}$$

Pressure ratio of compressor $r_p = \frac{P_{delivery}}{P_{suction}} = \frac{P_2}{P_1}$

WORK CONSUMPTION BY SINGLE STAGE RACWITH CLEARANCE

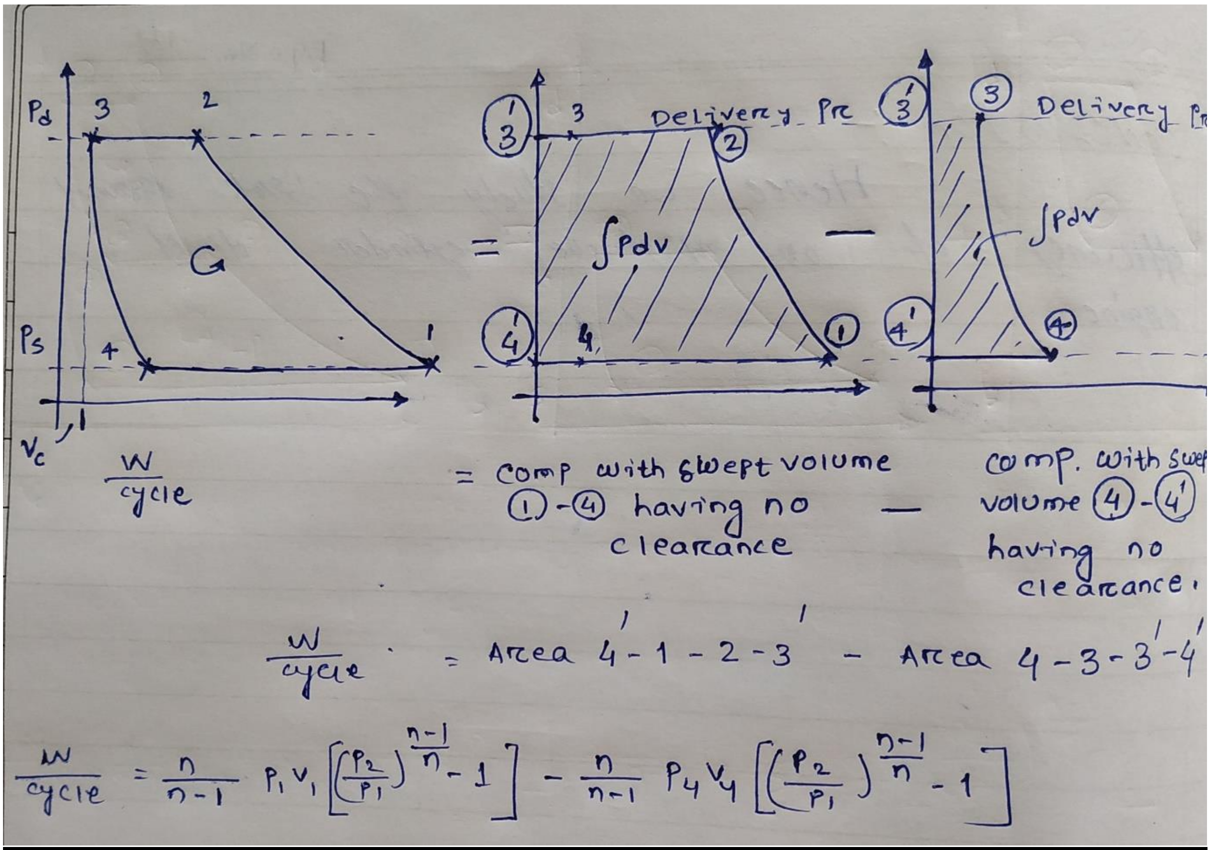


Figure 7 Indicator diagram showing Work consumed by a compressor having clearance volume

$$\frac{W}{cycle} = \frac{n}{n-1}[(\frac{P_2}{P_1})^{\frac{n-1}{n}} - 1][P_1V_1 - P_4V_4] \frac{kJ}{Cycle}$$

$$\frac{W}{cycle} = P_1(V_1 - V_4)\ [(\frac{P_2}{P_1})^{\frac{n-1}{n}} - 1] \frac{kJ}{Cycle}$$

$$\frac{W}{cycle} = \frac{n}{n-1} \times P_1(V_1 - V_4)\ [(\frac{P_2}{P_1})^{\frac{n-1}{n}} - 1] \frac{kJ}{Cycle}$$

Or you can use following formula for calculating consumption of work as per the data given

$$\frac{W}{cycle} = \frac{n}{n-1} \times\ m(\frac{kg}{cycle})R(T_1 - T_4)[(\frac{P_2}{P_1})^{\frac{n-1}{n}} - 1] \frac{kJ}{Cycle}$$

WORK CONSUMPTION BY TWO STAGE RACWITH CLEARANCE

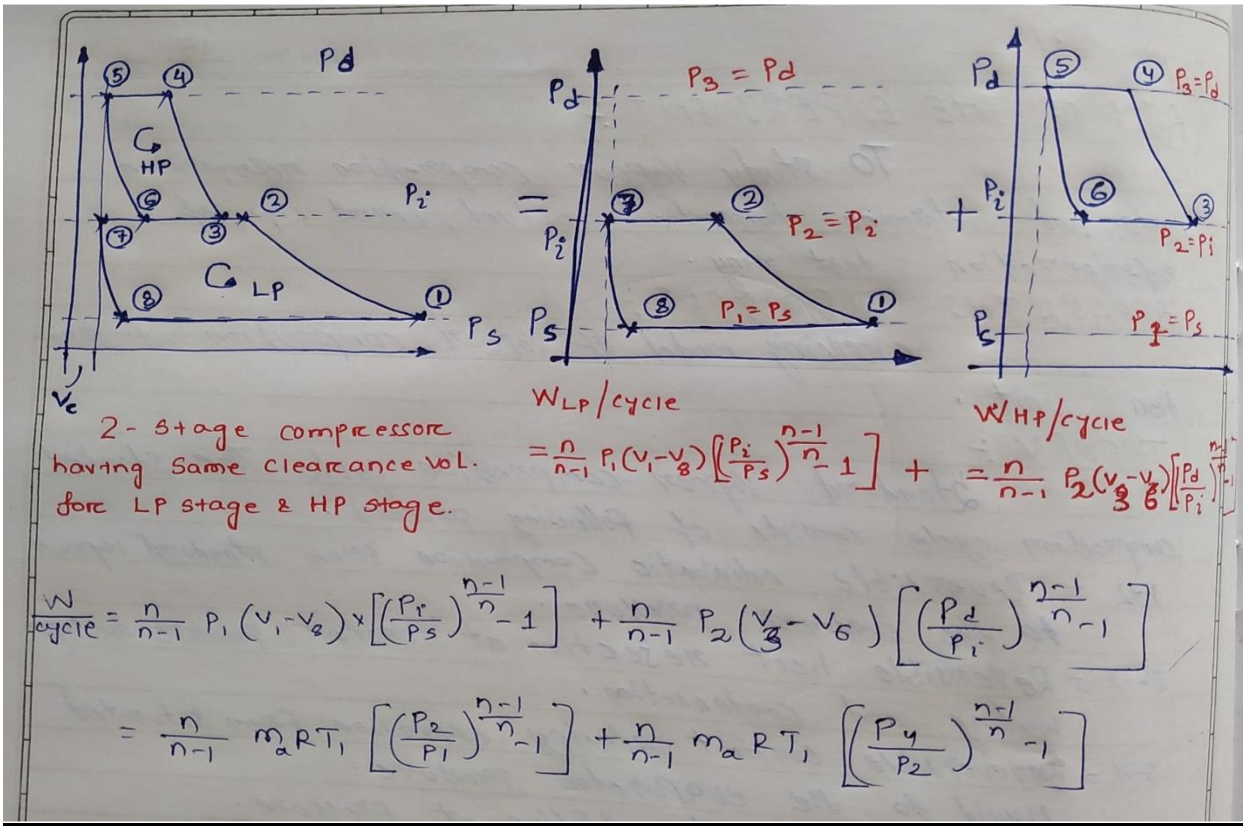


Figure 8 Indicator diagram showing work consumed by two stage compressor with same clearance volume for both low pressure and high-pressure stage

$$\frac{W}{cycle} = \frac{n}{n-1} \times P_1(V_1 - V_8)\left[\left(\frac{P_i}{P_s}\right)^{\frac{n-1}{n}} - 1\right] + \frac{n}{n-1} \times P_2(V_3 - V_6)\left[\left(\frac{P_d}{P_i}\right)^{\frac{n-1}{n}} - 1\right]$$

$$\frac{W}{cycle} = \frac{n}{n-1} \times m\left(\frac{kg}{cycle}\right)RT_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] + m\left(\frac{kg}{cycle}\right)RT_1\left[\left(\frac{P_4}{P_2}\right)^{\frac{n-1}{n}} - 1\right]\frac{kJ}{Cycle}$$

Assuming perfect intercooling i.e. $T_3 = T_1$

And same pressure ratio for Low pressure (LP) stage and High pressure (HP) stage

$$\frac{P_4}{P_2} = \frac{P_2}{P_1}$$

$$\frac{W}{cycle} = \frac{n}{n-1} \times m\left(\frac{kg}{cycle}\right)RT_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} + \left(\frac{P_4}{P_2}\right)^{\frac{n-1}{n}} - 2\right]\frac{kJ}{Cycle}$$

Or,

$$\frac{W}{cycle} = \frac{n}{n-1} \times P_1 V_1 (\frac{m^3}{cycle}) [(\frac{P_2}{P_1})^{\frac{n-1}{n}} + (\frac{P_4}{P_2})^{\frac{n-1}{n}} - 2] \frac{kJ}{Cycle}$$

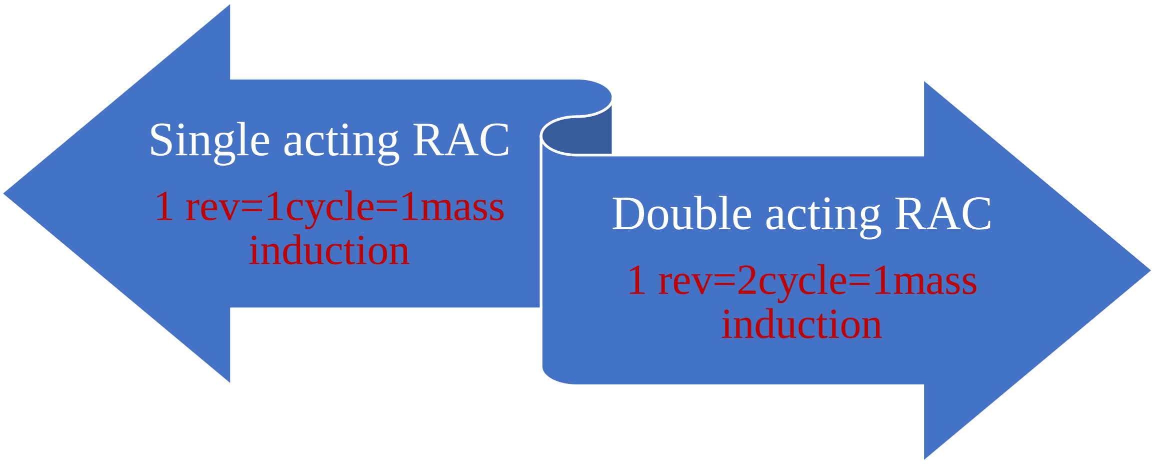


Figure 9 Difference from the context of mass induction for single and double acting RAC

FREE AIR DELIVERY (FAD)

- It is the volume of air delivered by compressor under the compressor intake conditions (i.e. local atmospheric temperature and pressure).
- In actual indicator diagram air is sucked at pressure and temperature lower than atmospheric condition
- Volume of air may be different but mass is same so putting conservation of mass principle

$\frac{P_f \times V_f}{T_f} = \frac{P_1 [V_1 - V_4]}{T_1}$ where P_f = Ambient pressure, V_f = free air delivery $(\frac{m^3}{min})$ and T_f is ambient temperature, P_1 = Suction pressure of compressor, V_1-V_4 = Effective swept volume $(\frac{m^3}{cycle})$ or volume of air induced $(\frac{m^3}{min})$ and T_1 =Suction temperature into compressor

So Free air delivery FAD = $V_f = \frac{P_1 T_f}{P_f T_1} \times [V_1 - V_4]$

VOLUMETRIC EFFICIENCY (η_V)

- It is the ratio of actual volume sucked into cylinder during suction stroke measured at atmospheric pressure and temperature to swept volume

$$\eta_v = \frac{fad}{V_{swept}}$$

- In some cases it is calculated in terms of

$$\eta_v = \frac{Effective\ swept\ volume}{Swept\ volume}$$

$$\eta_v = \frac{V_1 - V_4}{V_s}$$

$$\eta_v = \frac{V_C + V_S - V_4}{V_s}$$

$$\eta_v = \frac{V_c}{V_s} + \frac{V_s}{V_S} - \frac{V_4}{V_s}$$

$$\eta_v = 1 + c - [\frac{V_4}{V_S} \times \frac{V_C}{V_C}]$$

$$\eta_v = 1 + c - \frac{V_c}{V_S} \times [\frac{V_4}{V_C}]$$

$$\eta_v = 1 + c - C \times [\frac{V_4}{V_C}]$$

$$\eta_v = 1 + c - C \times \left(\frac{P_3}{P_4}\right)^{\frac{1}{n}} \qquad \text{Since } P_3 {V_3}^n = P_4 {V_4}^n$$

$$\eta_v = 1 + c - C \times \left(\frac{P_d}{P_S}\right)^{\frac{1}{n}}$$

PRACTICE SIMPLE PROBLEMS (WITHOUT CLEARANCE ONLY)

1. A single stage reciprocating air compressor takes in 1.4 kg of air per minute at 1 bar and17^0 C and delivers it at 6 bar. Assuming compression process follows the law $PV^{1.35}$ = C.
   Calculate (i) Indicated power input to compressor

2. A single acting 1-cylinder reciprocating air compressor has a cylinder diameter 200 mm and a stroke length of 300 mm. Air enters the cylinder at 1 bar 27^{0}C. It is then compressed polytropically to 8 bar and according to law $PV^{1.3}$ = c. speed of compressor is 250 RPM.
   Calculate (i) Mass of air compressed per minute
   (ii) Power required to drive the compressor

3. A single acting single cylinder reciprocating air compressor is compressing 20 kg/min of air from 110 kPa, 30^0C to 600 kPa. Law of compression is $PV^{1.25} = C$. Mechanical efficiency is 80%.
   Calculate (i) Power input to compressor

4. Single cylinder double acting reciprocating air compressor receives air at 1 bar and 17^0C, compresses to 6 bar. Law of compression is $PV^{1.25} = C$. Cylinder diameter is 300mm average piston speed is 150 meter/ min. Compressor runs at 100 RPM. Calculate (i) Power required in driving the compressor

5. Single stage single acting reciprocating air compressor takes in 1m3 air per minute at 1 bar and 17^0 C, delivers it at 7 bar. Compressor runs at 300 RPM. Law of compression is $PV^{1.35} = C$. η_{mech} = 85%. Motor transmission or electrical efficiency η_{elect} = 90%. Compressor stroke to bore ratio is 1.5.
   Calculate (i) Power required to drive the compressor
   (ii) Cylinder bore dia
   (iii) Cylinder stroke length

6. A single acting single cylinder reciprocating air compressor has a cylinder diameter of 300 mm and a stroke of 400 mm. It runs at 100 RPM. Air enters the cylinder at 1 bar, 200C. It is then compressed to 5 bar.
   Calculate (i) mean effective pressure
   (ii) Indicated power to compressor if law of compression is PV = C
   (iii) Indicated power to compressor if law of compression is $PV^{1.2} = C$
   (iv) Indicated power to compressor if law of compression is $PV^{1.4} = C$
   (v) Show in which process compressor consumes least work and justify.