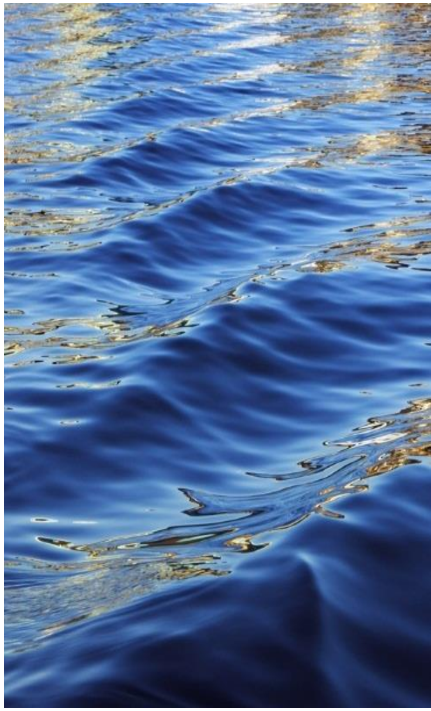
Environmental Thermal Engineering

Lecture Note #3

Professor Min Soo KIM



Compressor

The Main Contents of the Compressor

- Overview of Compressor
- Types of Compressor
- Reciprocating Compressor
- Ideal Compressor Performance
- Actual Compressor Performance

Overview of Compressor

- One of the most important components for refrigeration and air conditioning.

- A compressor is a machine that compresses a working gas to increase pressure by receiving power from an electric motor or a turbine power device and applying a compression work to air or refrigerant.

- It is used for refrigerant compressors, ventilation of buildings with low pressure, supercharging of automobile engines, compression of working fluid in power generation cycles, etc.

Types of Compressor

- **Positive Displacement Compressor**

  → Pressure increase through volume reduction

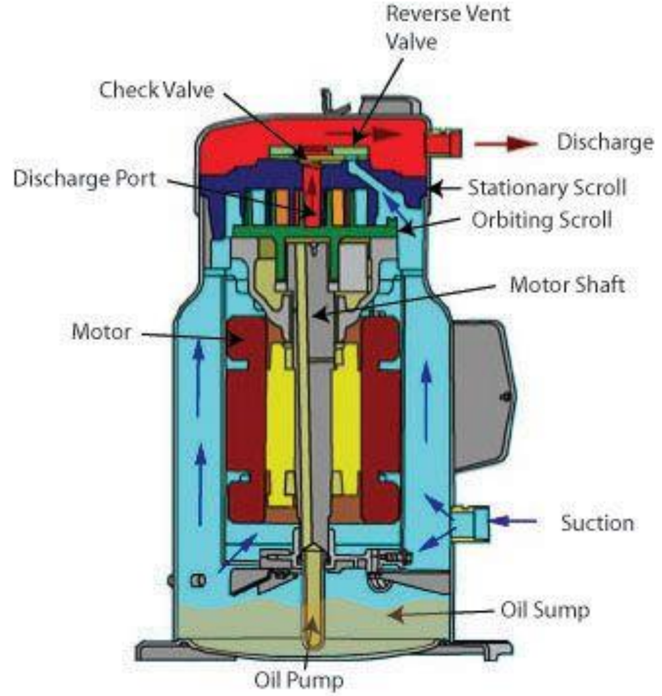
- **Turbo Compressor**

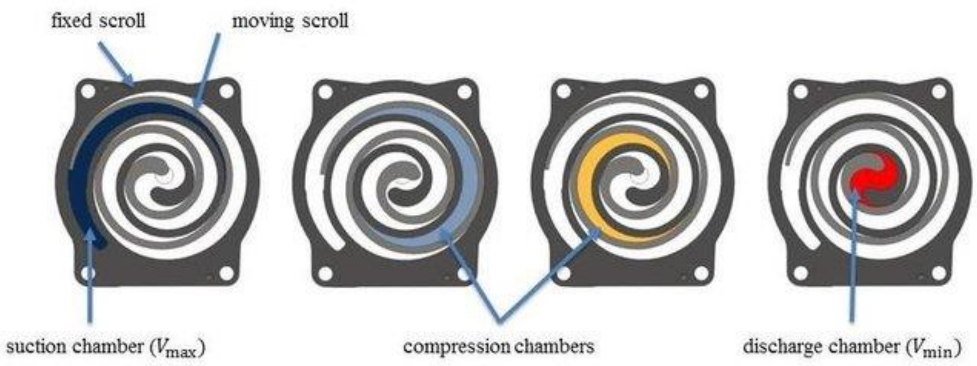
  → Compression by converting the kinetic energy of gas into the form of pressure energy

- Compressor
  - Volumetric
    - Reciprocating
    - Rotary, Scroll, Screw
  - Turbo type
    - Centrifugal
    - Axial

Types of Compressor

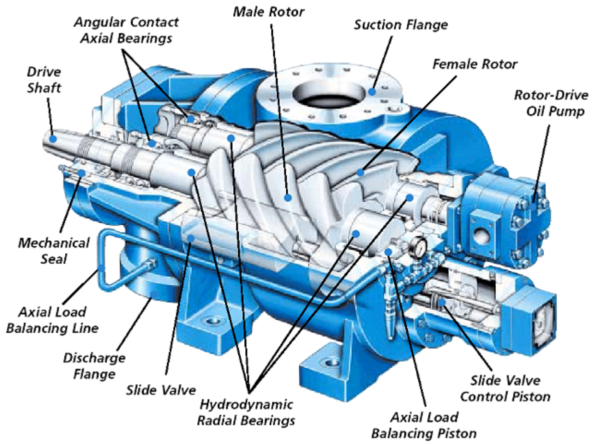
Scroll Compressor

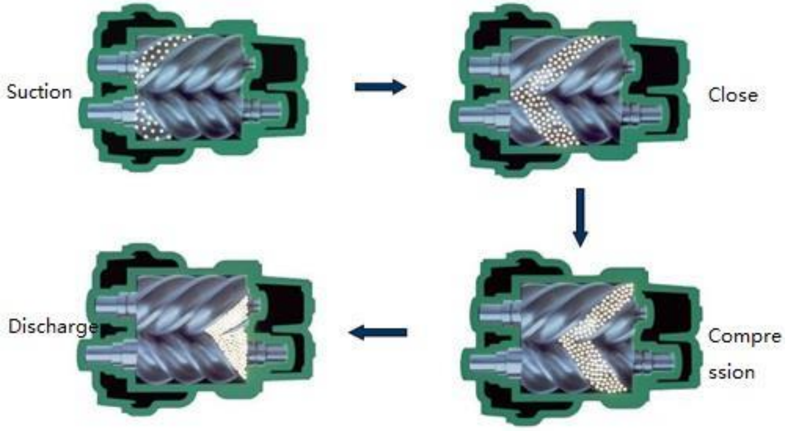




Types of Compressor

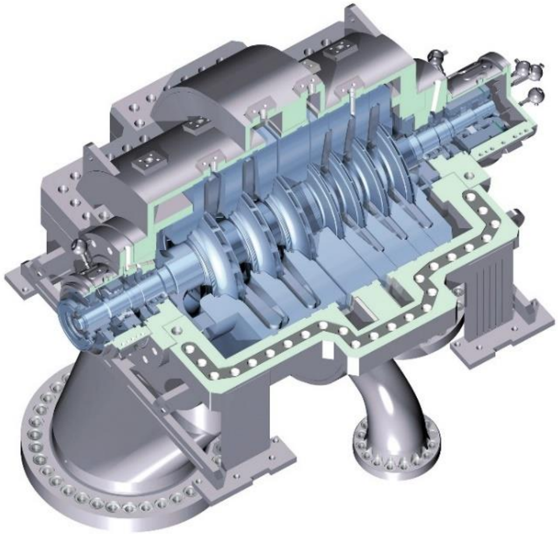
Screw Compressor

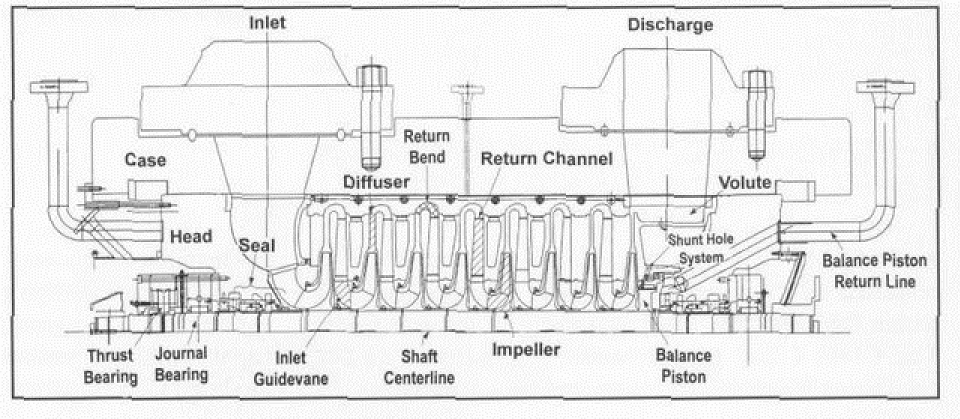




Types of Compressor

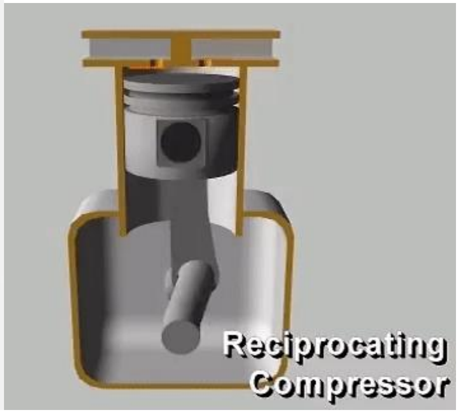
Centrifugal Compressor

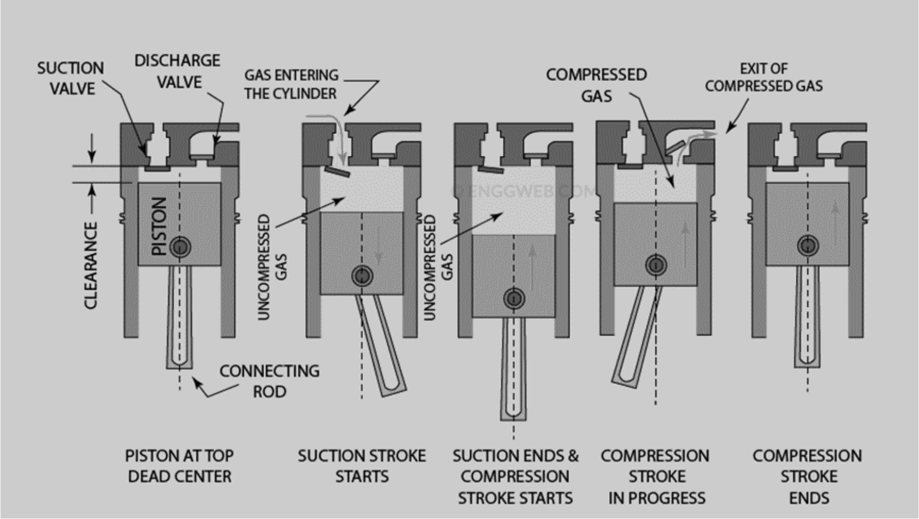




Types of Compressor

Reciprocating Compressor





The Scope of Application of Compressor

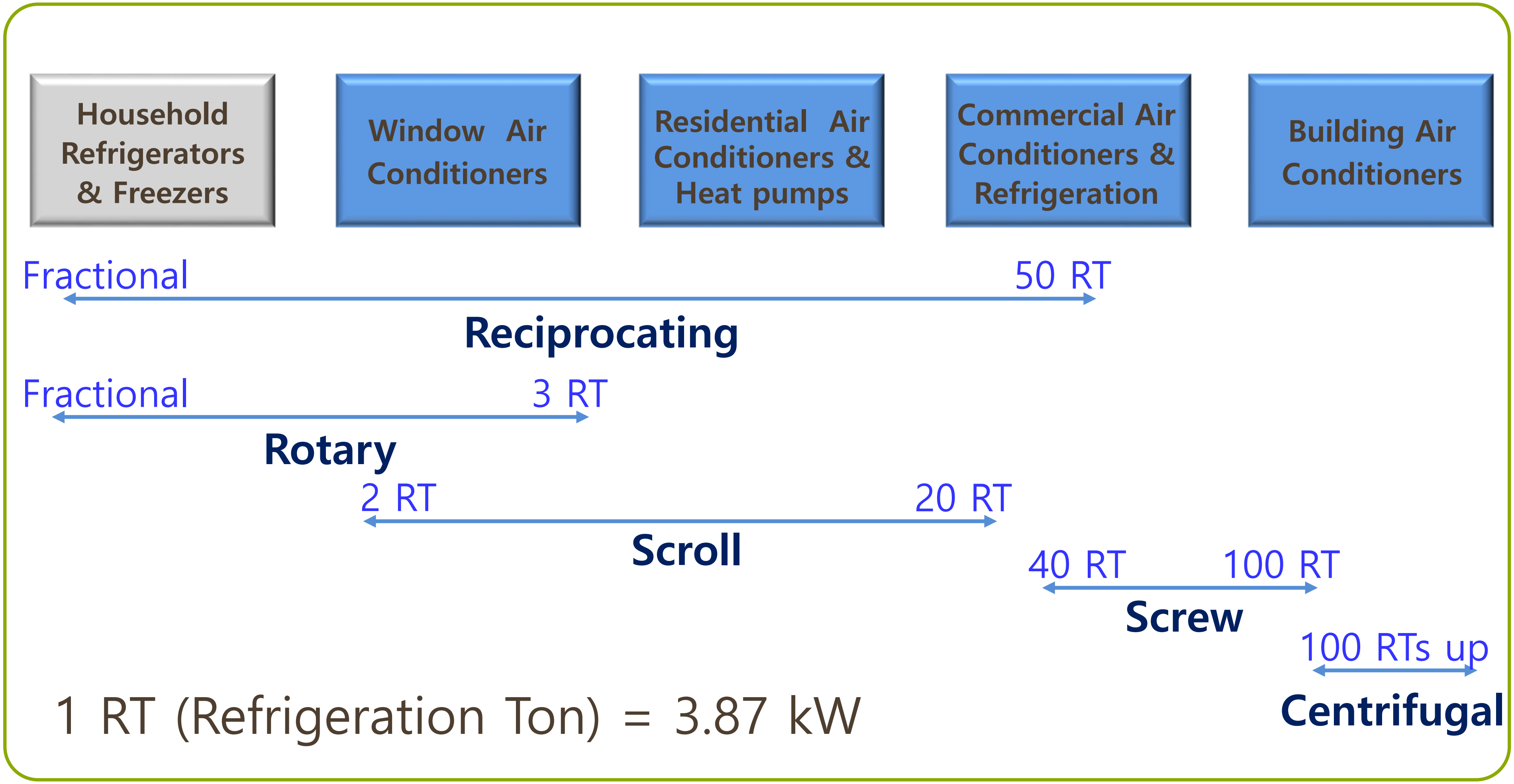


FIGURE Range of Applications of Compressor on Refrigerating Capacity

Types of Compressor

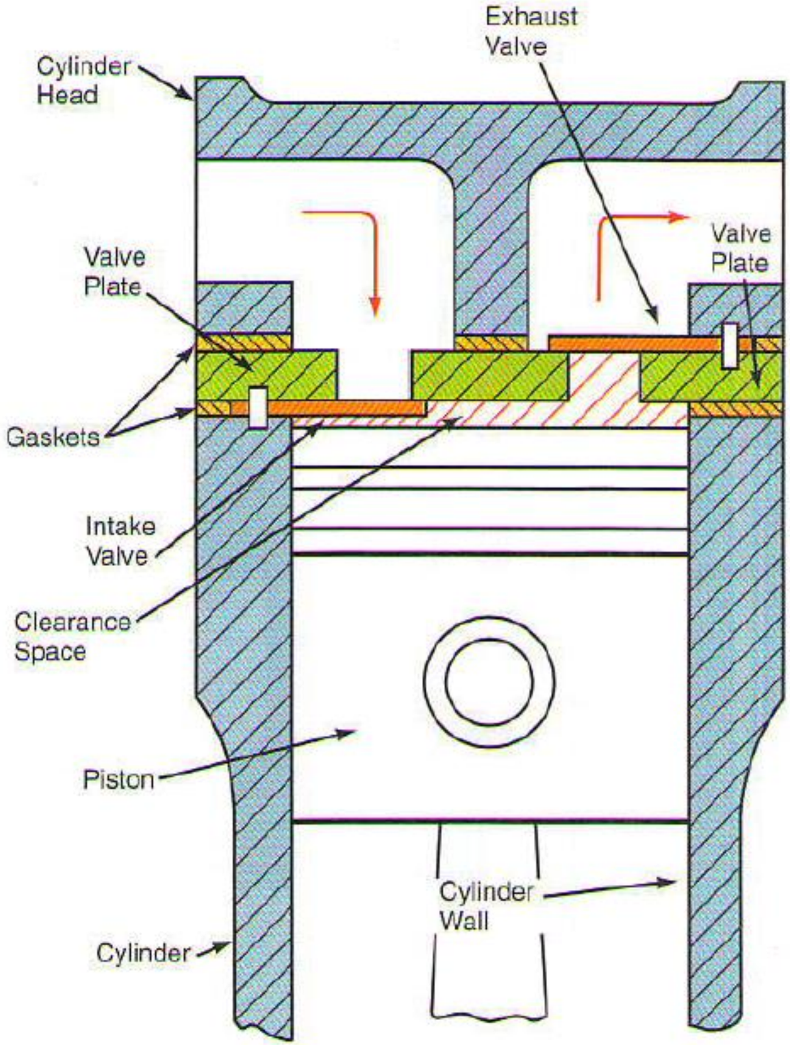
- Open Type Compressor
  - Compressor passing through the compressor housing so that the motor can be externally coupled to the shaft.
  - Refrigerant gas leakage problem
- Hermetic Compressor
  - Eliminates leakage problems by installing the motor within the housing of the compressor
  - Requires electrical isolation of the motor
- Semi-Hermetic Compressor
  - Bolted Compressor for Field Repair

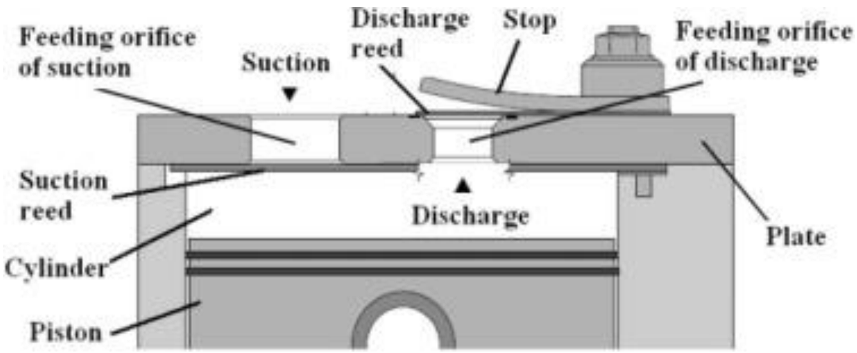
Open Type Compressor

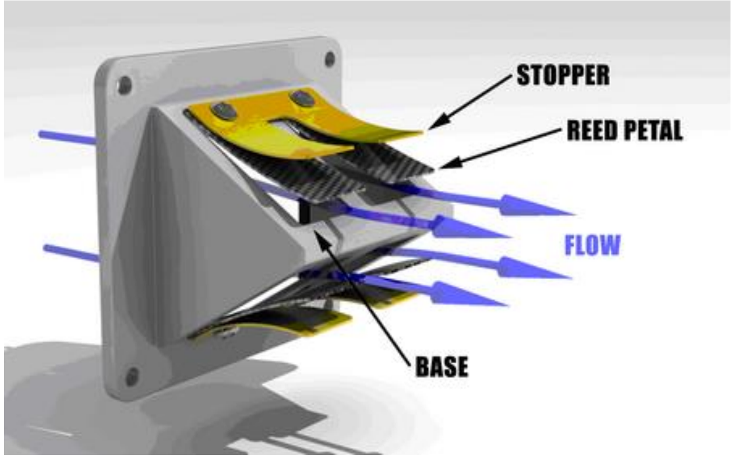
Hermetic Compressor

Compressor

Cross-sectional View



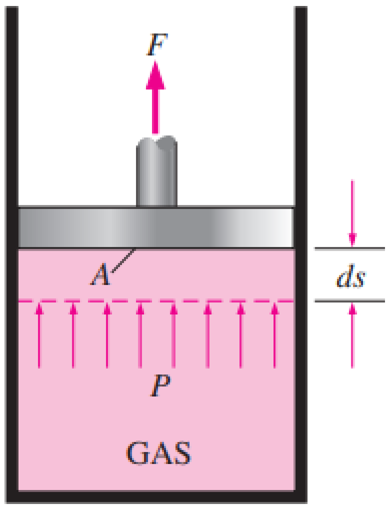




Compressor

Thermodynamics Review

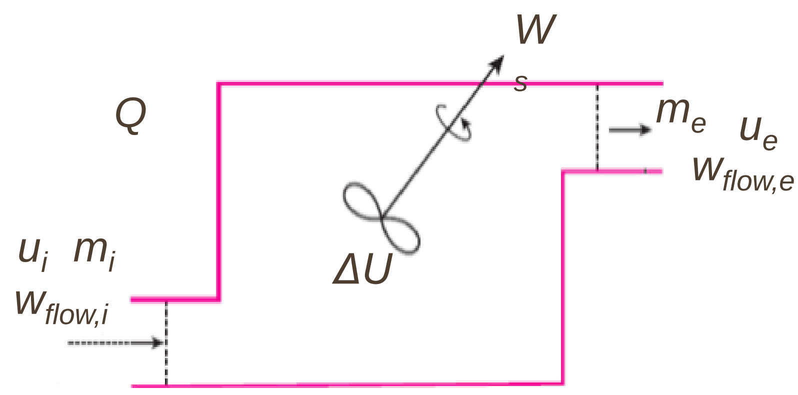
Closed system



$$W_b = \int F\, ds = \int PA\, ds$$

$$\boxed{W = \int PdV}$$

Open system



$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}\left(h + \frac{V^2}{2} + gz\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}\left(h + \frac{V^2}{2} + gz\right)$$

$$W = H_i - H_e + Q \cdots (1)$$

$$H = U + PV \qquad dH = dU + VdP + PdV$$

$$\delta Q = dU + PdV$$

$$Q = H_e - H_i - \int_i^e VdP \cdots (2)$$

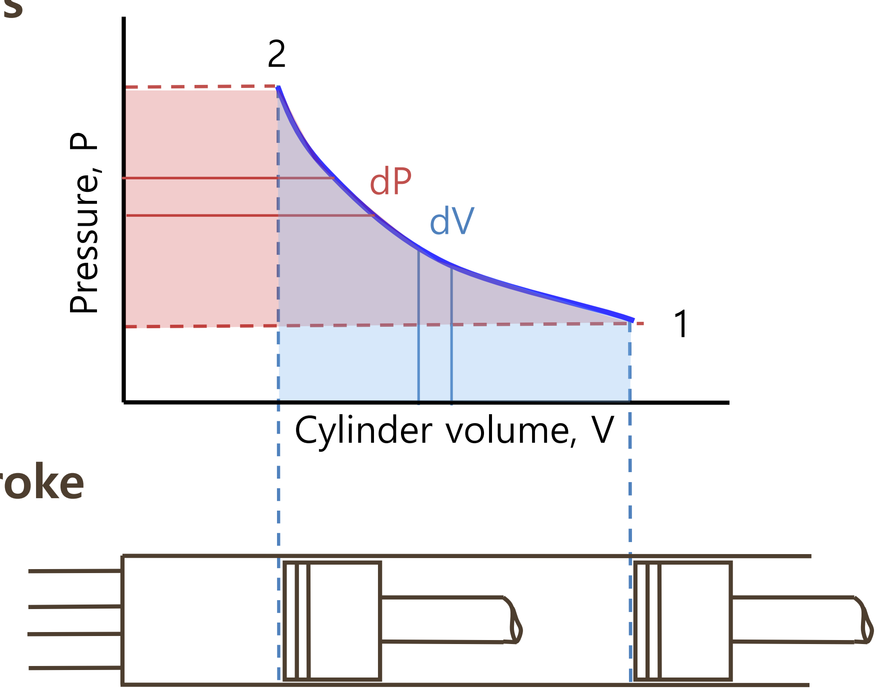
$Substituting\ (2)\ in\ (1),$ $\boxed{W = -\int_i^e VdP}$

Compressor Work

Compression Work

- Work required to compress a gas from P_1 to P_2

$$W' = \int_{V_1}^{V_2} P dV$$



Compressor Work

- Work done on working gas by compressor during the entire stroke
- Sum of compression, discharge, and suction work.

$$W_{comp,in} = \int_{P_1}^{P_2} V dP \qquad where \quad W_{rev} = -\int_{P_1}^{P_2} V dP$$

Types of Compression

Isothermal Compression

$$PV = C(constant)$$

Compression Work $$W'_{iso} = P_1V_1 \ln\frac{P_1}{P_2}$$

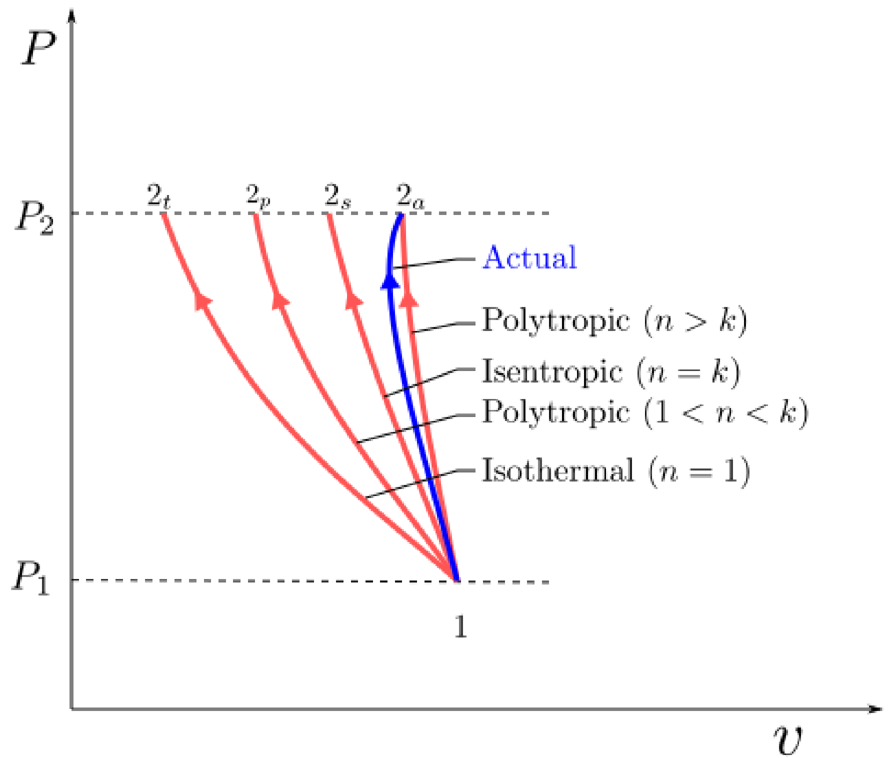
Compressor Work $$W_{iso} = -W'_{iso} = P_1V_1 \ln\frac{P_2}{P_1}$$

$$W' = \int_{V_1}^{V_2} PdV = \int_{V_1}^{V_2} \frac{C}{V} dV = Cln\frac{V_2}{V_1}$$

$$= P_1V_2 \ln\frac{V_2}{V_1} = P_1V_2 \ln\frac{P_1}{P_2}$$

$$W = \int_{P_1}^{P_2} VdP = \int_{P_1}^{P_2} \frac{C}{P} dP = Cln\frac{P_2}{P_1}$$

$$= P_1V_2 \ln\frac{P_2}{P_1}$$



Compressor

Types of Compression

Isentropic Compression

$$PV^k = const \qquad T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

Compression Work $$W'_{isen} = \frac{-P_1V_1}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right]$$

Compressor Work $$W_{isen} = \frac{kP_1V_1}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right]$$

$$W_{isen} = \int_{V_1}^{V_2} V\,dP = \int_{V_1}^{V_2} \frac{C^{\frac{1}{k}}}{P^{\frac{1}{k}}}\,dP$$

$$= \frac{C^{\frac{1}{k}}}{1-\frac{1}{k}}\left(P_2^{\frac{k-1}{k}} - P_1^{\frac{k-1}{k}}\right)$$

$$= C^{\frac{1}{k}}\frac{k}{k-1}P_1^{\frac{k-1}{k}}\left(\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right)$$

$$= \frac{kP_1V_1}{k-1}\left(\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right)$$

Types of Compression

Polytropic Compression

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

Compression Work $$W'_{pol} = \frac{-P_1V_1}{n-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

Compressor Work $$W_{pol} = \frac{nP_1V_1}{n-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$W_{poly} = \int_{V_1}^{V_2} V\,dP = \int_{V_1}^{V_2} \frac{C^{\frac{1}{n}}}{P^{\frac{1}{n}}}\,dP$$

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

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

$$= \frac{nP_1V_1}{n-1}\left(\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right)$$

Reciprocating Compressor

- **Most widely used in the "Refrigeration Industry**

- **Refrigeration Range**

  Wide Range
  (Small size to tens of kW)

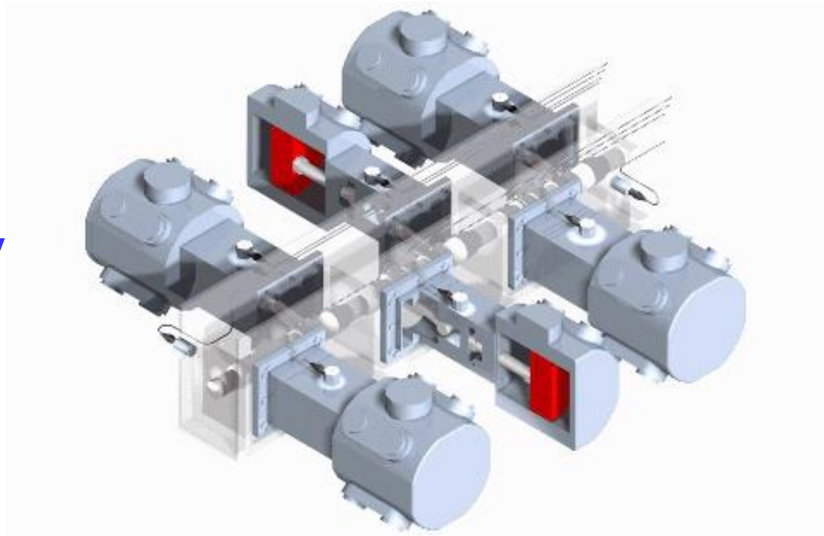
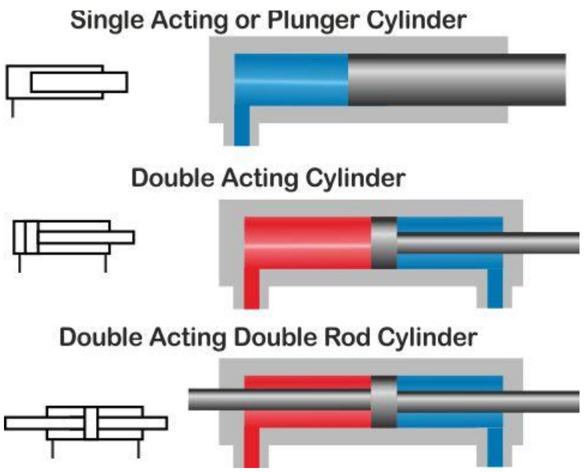


Figure Reciprocating Compressor

- **Types**

  Single-acting, Double-acting



- **Working Principle**

  connected through a connecting rod and
  a pin from the crankshaft actuated by piston

Reciprocating Compressor

Ideal reciprocating compressor (Process : 2s)

It is assumed that the compression process is reversibly adiabatic without pressure loss through suction and discharge ports and other valves.

Actual reciprocating compressor (Process : 2a)

Different from the ideal compressor, some losses occur, and these points must be taken into account in the performance of the compressor.

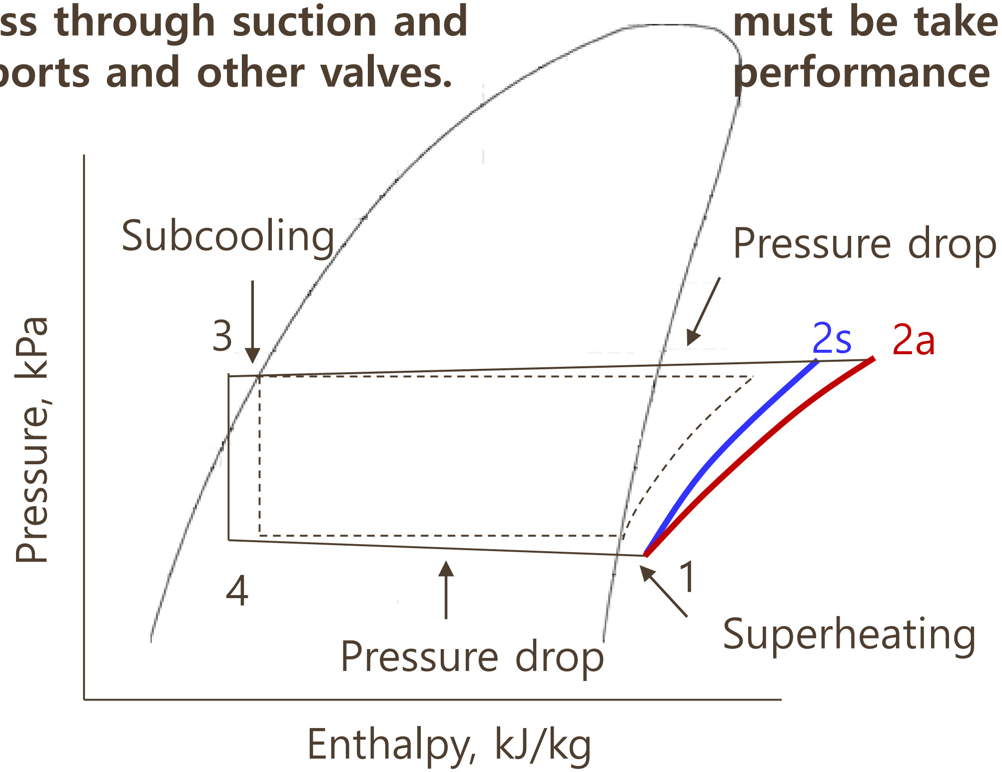


Figure The comparison of isentropic compression and actual compression

Performance of Reciprocating Compressor

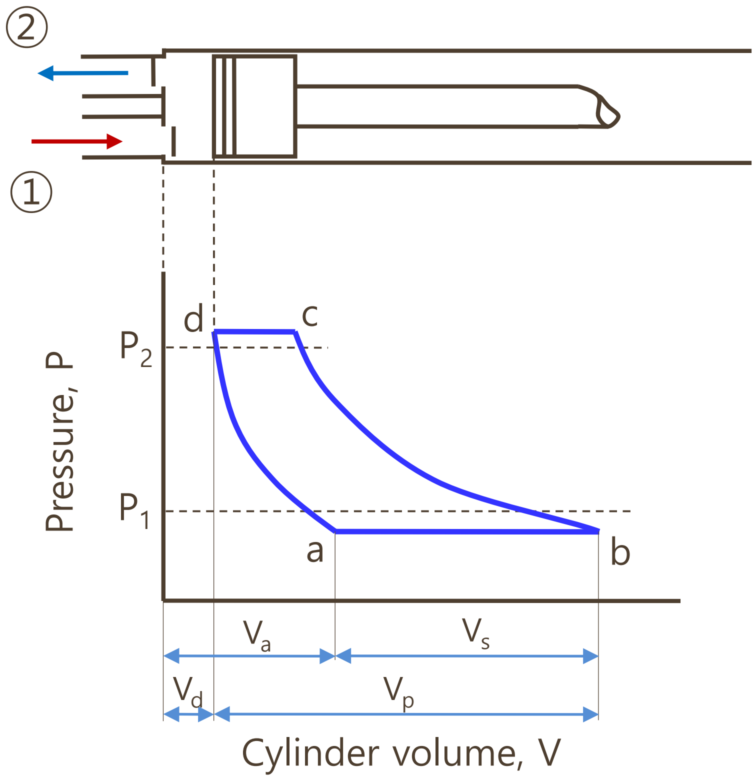


Figure Schematic Indicator Diagram for a Reciprocating Compressor

It is assumed that the pressure in the cylinder is constant (P_c = P_d, P_a = P_b) during the discharge and suction processes.

The pressure loss that occurs as it passes through the valve is taken into account.

Performance of Reciprocating Compressor

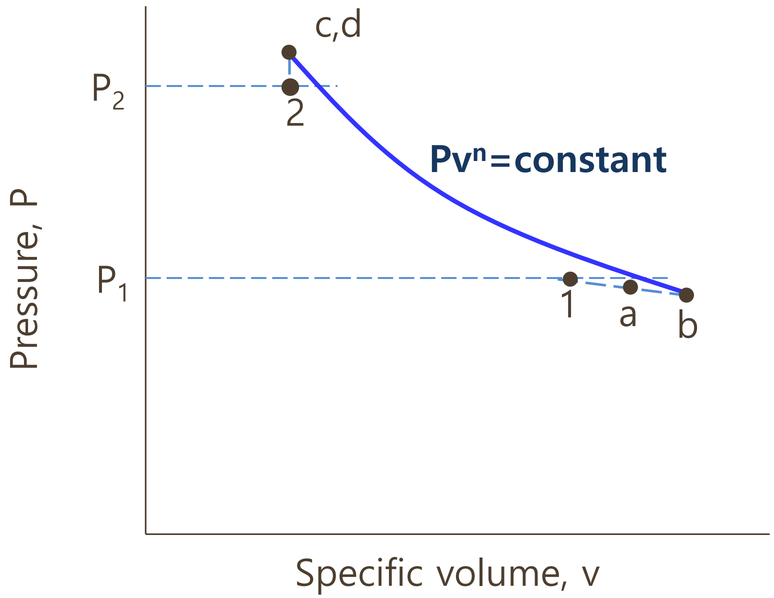


Figure Pressure-Specific Volume Diagram for Compressor

P_c (Start of discharge) = P_d (End of discharge)

P_2 : Discharge gas (After valve)

P_1 : Suction gas (Before valve)

P_a : Start of suction

P_b : End of suction

a → b Re-expansion caused by residual gas in the process

Volumetric Efficiency

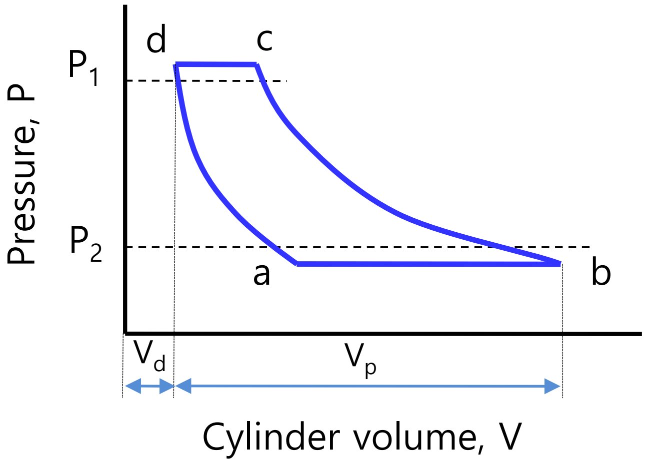
Clearance volume

➡ When the piston reaches top dead center, there is a slight clearance at the top

Gas Volume Ratio

➡ Ratio of clearance and stroke volume

$$C = \frac{V_d}{V_p}$$



- After the compression and discharge strokes are completed, the fluid in the gap volume expands during the suction stroke, and the volume flowing into the compressor decreases as much as the expansion of the residual gas.

➡ **Re-expansion loss occurs**

Volumetric Efficiency

Volumetric Efficiency

$$\eta_{vol} = \frac{Actual\ refrigerant\ intake}{Theoretical\ refrigerant\ Intake}$$

$$= \frac{V_s/v_b}{V_p/v_1} = \frac{V_p - (V_a - V_d)}{V_p}\frac{v_1}{v_b}$$

If the process at points d~a is a polytropic

$$V_a = V_d\left(\frac{P_d}{P_a}\right)^{\frac{1}{n}} = V_d\left(\frac{P_c}{P_b}\right)^{\frac{1}{n}}$$

The polytropic index **n** is determined by the experimental value.

$$\eta_{vol} = \frac{V_p - (V_a - V_d)}{V_p}\frac{v_1}{v_b} = 1 - \frac{V_a - V_d}{V_p}\frac{v_1}{v_b}$$

$$\eta_{vol} = \left\{1 - C\left[\left(\frac{P_c}{P_b}\right)^{\frac{1}{n}} - 1\right]\right\}\frac{v_1}{v_b} \qquad where\ C = \frac{V_d}{V_p}$$

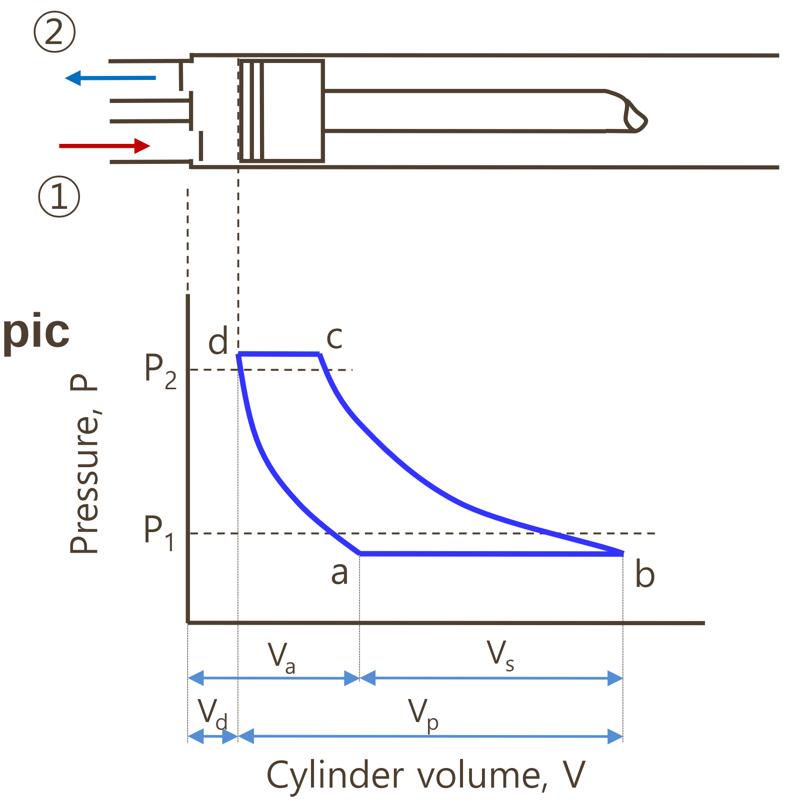


Figure Schematic Indicator Diagram for a Reciprocating Compressor

Volumetric Efficiency and Mass Flow Rate

If the re-expansion and compression processes are isentropic,

Volumetric Efficiency

$$\eta_{vol} = \left[1 - C\left\{\left(\frac{P_c}{P_b}\right)^{\frac{1}{n}} - 1\right\}\right]\frac{v_1}{v_b} = \left[1 - C\left\{\left(\frac{v_b}{v_c}\right) - 1\right\}\right]\frac{v_1}{v_b}$$

Isentropic index k value

R12=1.13, R22=1.16

Mass Flow Rate

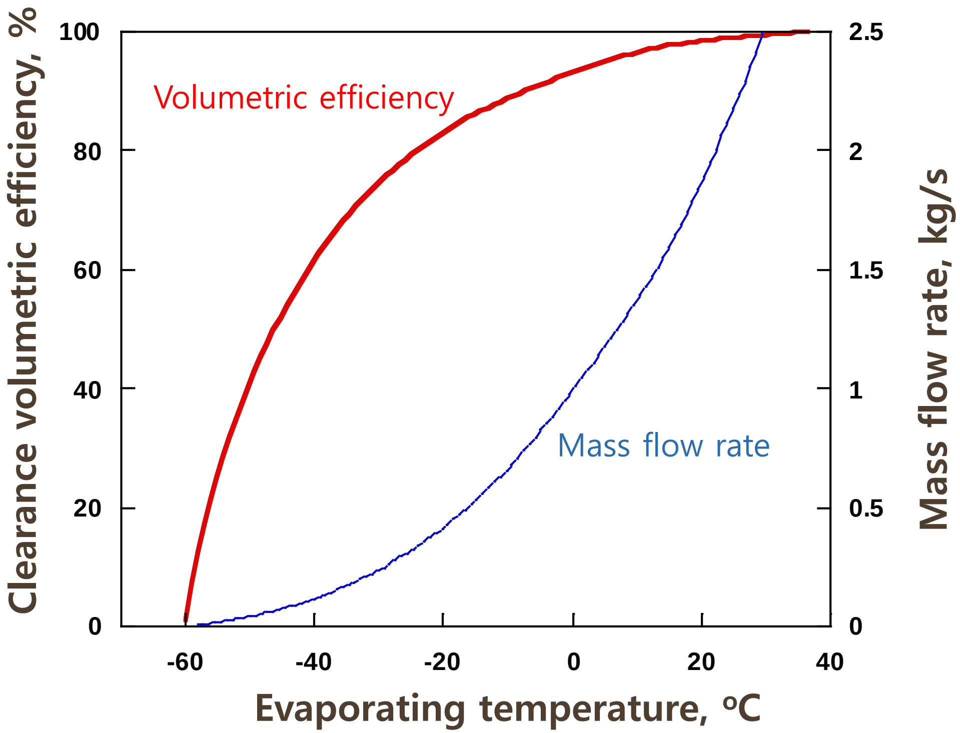
$$\dot{m} = \eta_{vol}\frac{V_p}{v_1}N_c = \left[1 - C\left\{\left(\frac{P_c}{P_b}\right)^{\frac{1}{n}} - 1\right\}\right]\frac{V_p}{v_b}N_c$$

V_p : Piston displacement [m^3]

N_c : Crankshaft revolution [1/s]

Volumetric Efficiency and Mass Flow Rate

Volumetric Efficiency and Mass Flow Rate



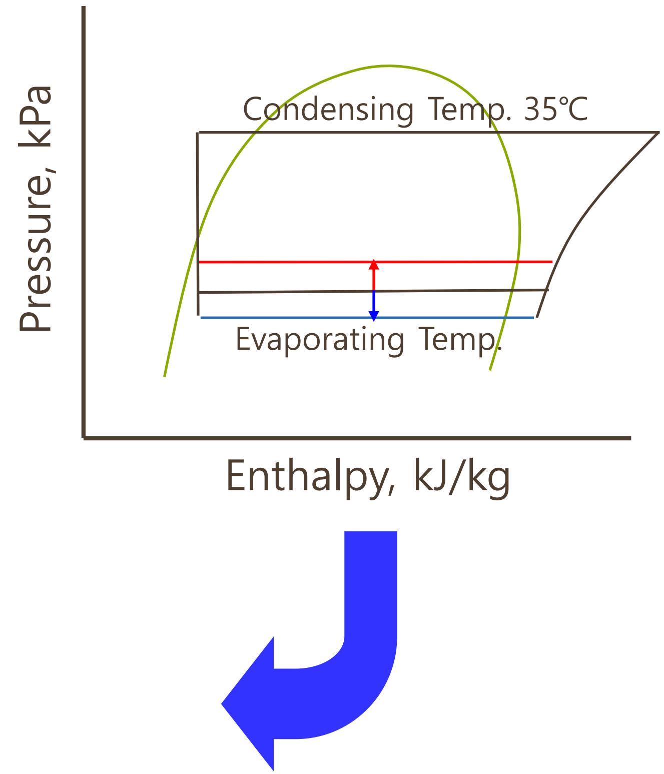
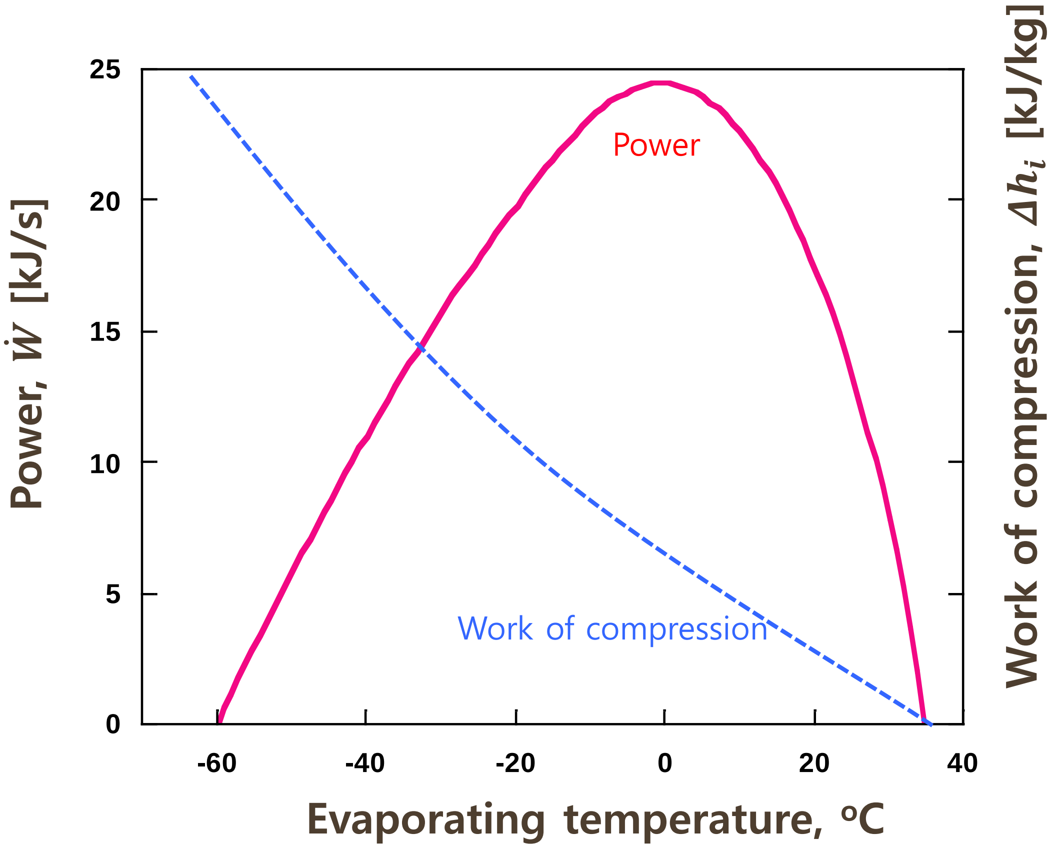


Figure Clearance Volumetric Efficiency and Mass Flow Rate of Ideal Compressor, Refrigerant 22, 4.5% Clearance, 50 L/s Displacement Rate, and 35℃ Condensing Temperature

Required Power

- **Power Requirement for Compressor** $\dot{W} = \dot{m}\Delta h_i$



Compressor

Refrigeration Capacity and COP

- **Refrigeration Capacity** $\dot{Q} = \dot{m}(h_1 - h_4)$
- **Coefficient of Performance** $COP_c = \frac{\dot{Q}}{\dot{W}} = \frac{(h_1 - h_4)}{\Delta h_i} = \frac{Refrigeration\ Capacity}{Required\ Work}$

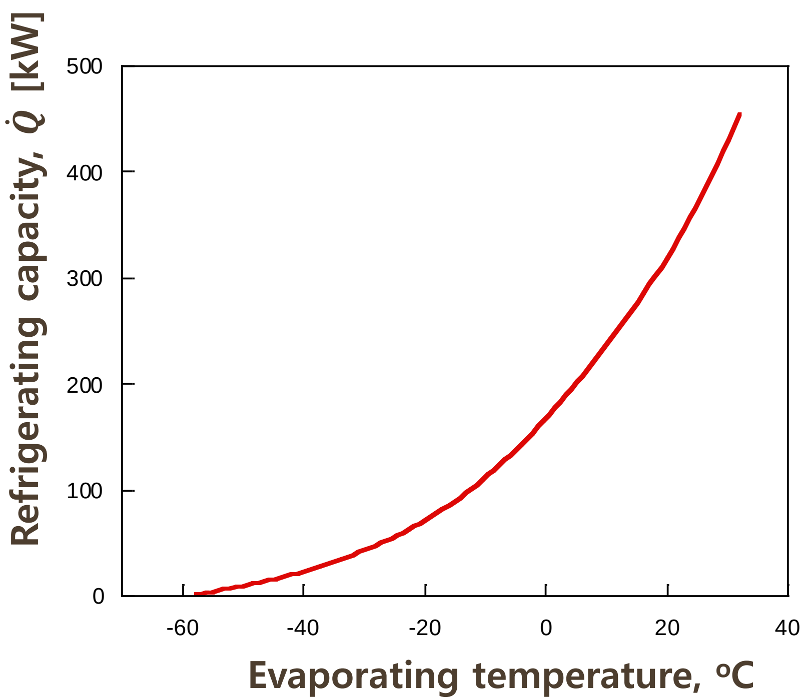


Figure Cooling Capacity according to evaporation temperature

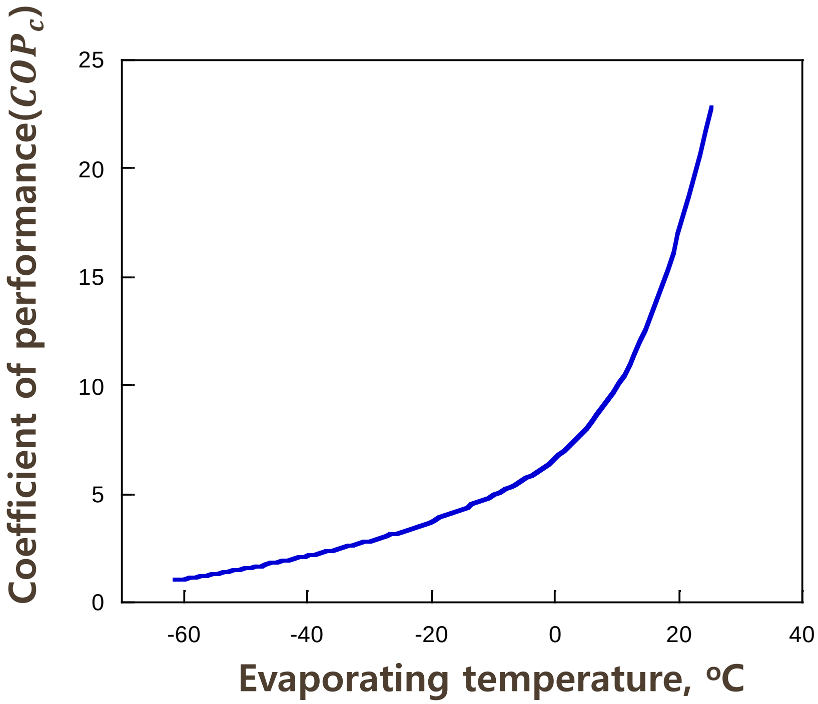


Figure COP according to evaporation temperature

Compressor

Actual Compressor Performance

- Performance trends for ideal compressors also exist for real compressors
- Power required

➡ **Theoretical power required (Adiabatic case)**

$$W_o = \frac{kP_bV_b}{k-1}\left[\left(\frac{P_c}{P_b}\right)^{\frac{k-1}{k}} - 1\right]$$

Isentropic Compression

$$PV^k = const \qquad T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

Compression Work $\quad W'_{isen} = \frac{-P_1V_1}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right]$

Compressor Work $\quad W_{isen} = \frac{kP_1V_1}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right]$

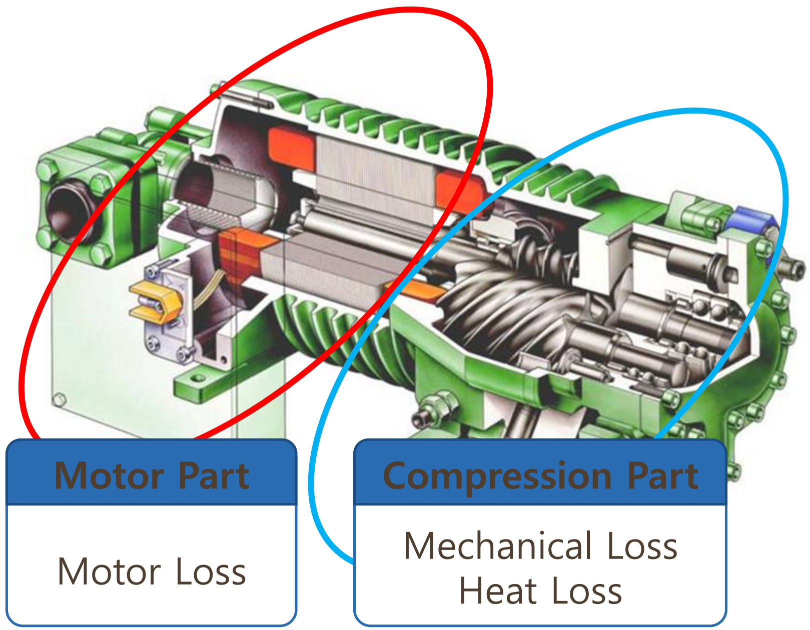
➡ **Actual power required**

$$W_s = \frac{W_o}{\eta_c\eta_{mech}} = \frac{1}{\eta_c\eta_{mech}}\frac{kP_bV_b}{k-1}\left[\left(\frac{P_c}{P_b}\right)^{\frac{k-1}{k}} - 1\right]$$

η_c : Compression Efficiency (W_o/W)

η_{mech} : 0.85 ~ 0.95

Compressor Efficiency



Power Required by Compressor	η_{motor}		η_{mech}		Work sed for Refrigerant compression
ex) 100	× $\frac{90}{100}$		× $\frac{80}{90}$	→	$\frac{80}{100}$

$$\eta_{comp} = \eta_{moter} \cdot \eta_{mech} = 0.8$$

Question and Answer Session