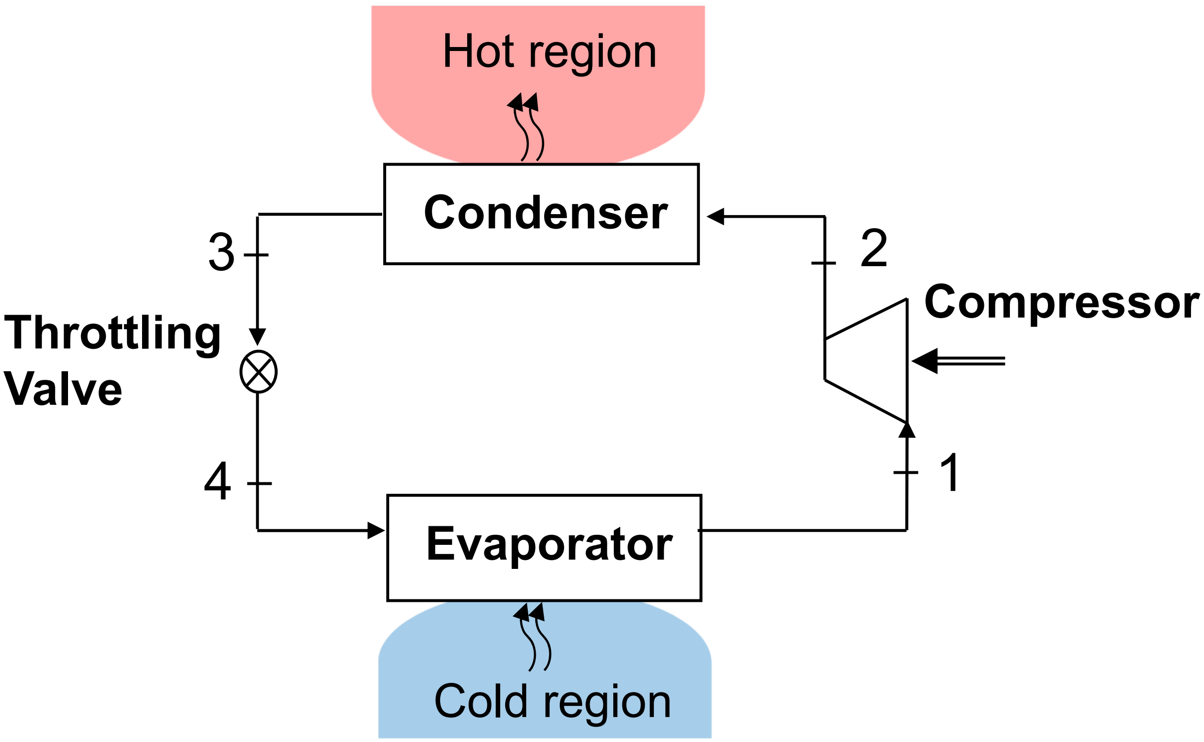
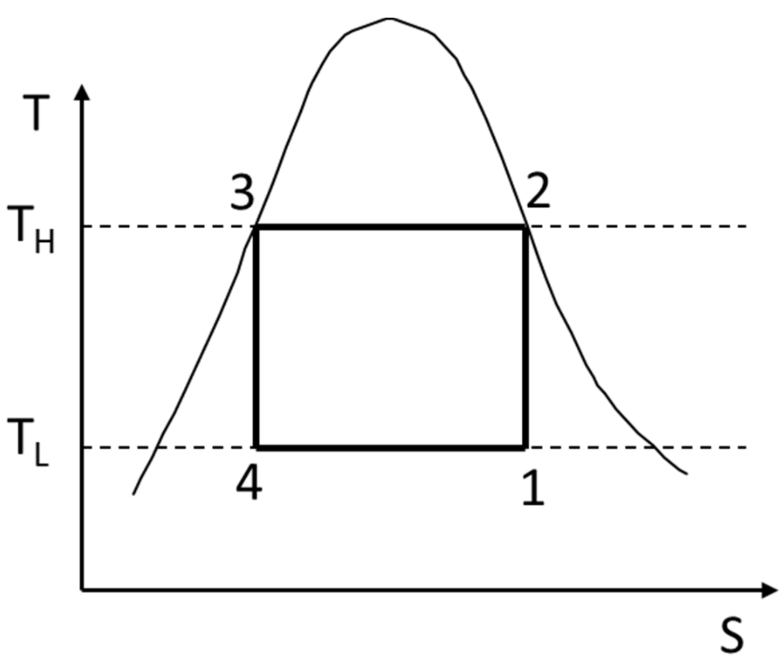
ME 418
Lecture 13 - Vapor Compression Equipment - I
In-Class Notes for Fall 2024

- Review of vapor compression systems
- Refrigerant
- Compressors

Vapor Compression Systems

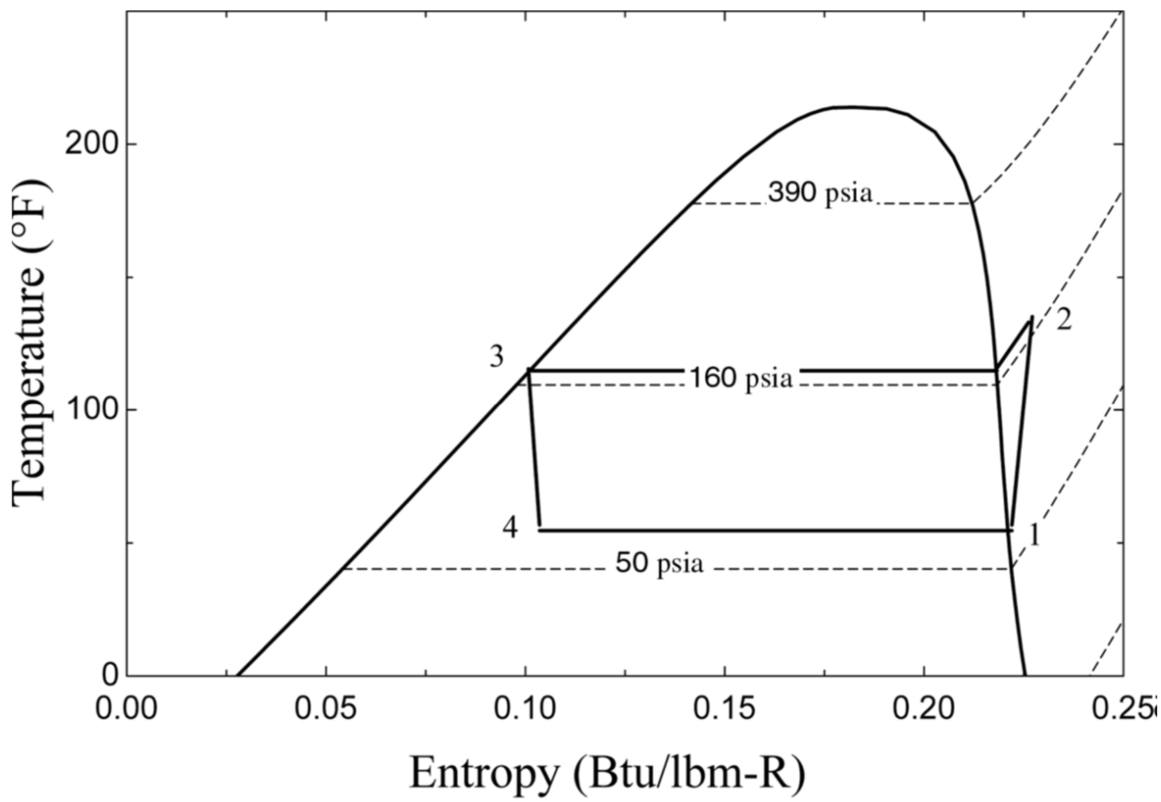


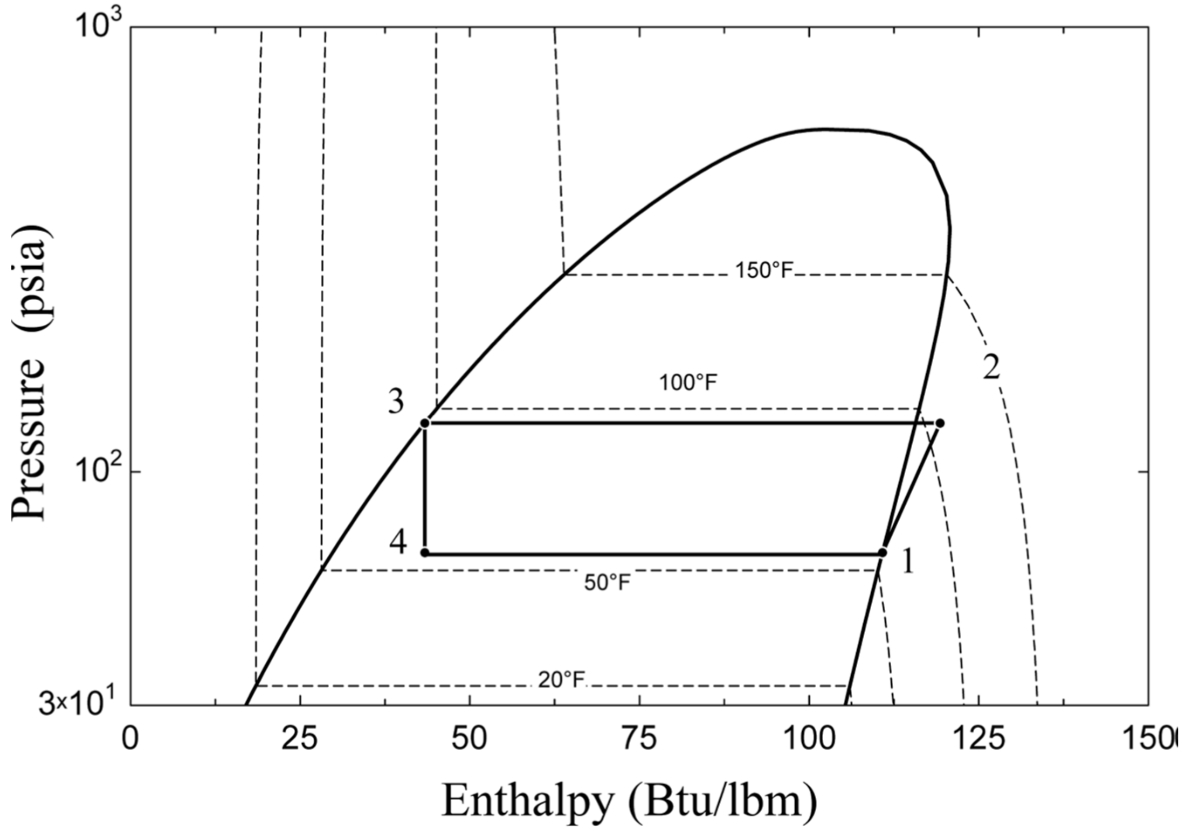


Carnot (idealized) refrigeration system COP

$$COP_{Carnot} = \frac{\dot{Q}_L}{\dot{W}_{ideal}} = \frac{T_L}{T_H - T_L}$$

Actual Vapor Compression Cycle





Process 1-> 2: Adiabatic compression
Process 2-> 3: Condensation at constant pressure
Process 3-> 4: Adiabatic and isenthalpic throttling
Process 4-> 1: Evaporation at constant pressure

Energy Balances on Components

Compressor work

$$\dot{W}_c = \dot{m}\left(h_2 - h_1\right)$$

Isentropic work

$$\dot{W}_s = \dot{m}\left(h_{2s} - h_1\right)$$

Isentropic efficiency

$$\eta_s = \frac{\dot{W}_s}{\dot{W}_c}$$

Condenser heat transfer

$$\dot{Q}_c = \dot{m}\left(h_2 - h_3\right)$$

Evaporator heat transfer

$$\dot{Q}_e = \dot{m}\left(h_1 - h_4\right)$$

Expansion process

$$h_3 = h_4$$

Refrigeration system

$$\dot{Q}_e + \dot{W}_c = \dot{Q}_c$$

System COP

$$COP = \frac{\dot{Q}_e}{\dot{W}_c} = \frac{\dot{m}\left(h_1 - h_4\right)}{\dot{m}\left(h_2 - h_1\right)}$$

Vapor-Compression Cycle Example: A vapor compressor cycle uses R-134a as the working fluid and operates between a cold fluid at a temperature of 55 F and a warm fluid at a temperature of 95 F. Determine the cooling produced, work required, and COP for

a) a compressor efficiency of 100 % and no temperature difference between the source or sink fluid and the refrigerants in the heat exchangers,
b) for a compressor with a 70 % efficiency,
c) a 10 F temperature difference for heat transfer in both the condenser and the evaporator,
d) all of the effects taken together
e) Determine the COP of a Carnot cycle for these temperatures.

Refrigerants

1st Generation ‘Whatever worked’ — 1830 - 1930

- Industrial applications
- Toxic, flammable
- Examples:
  - NH3
  - CO2
  - Hydrocarbons
  - H2O
  - SO2

2nd Generation ‘Safe & stable’ — 1930 - 1990

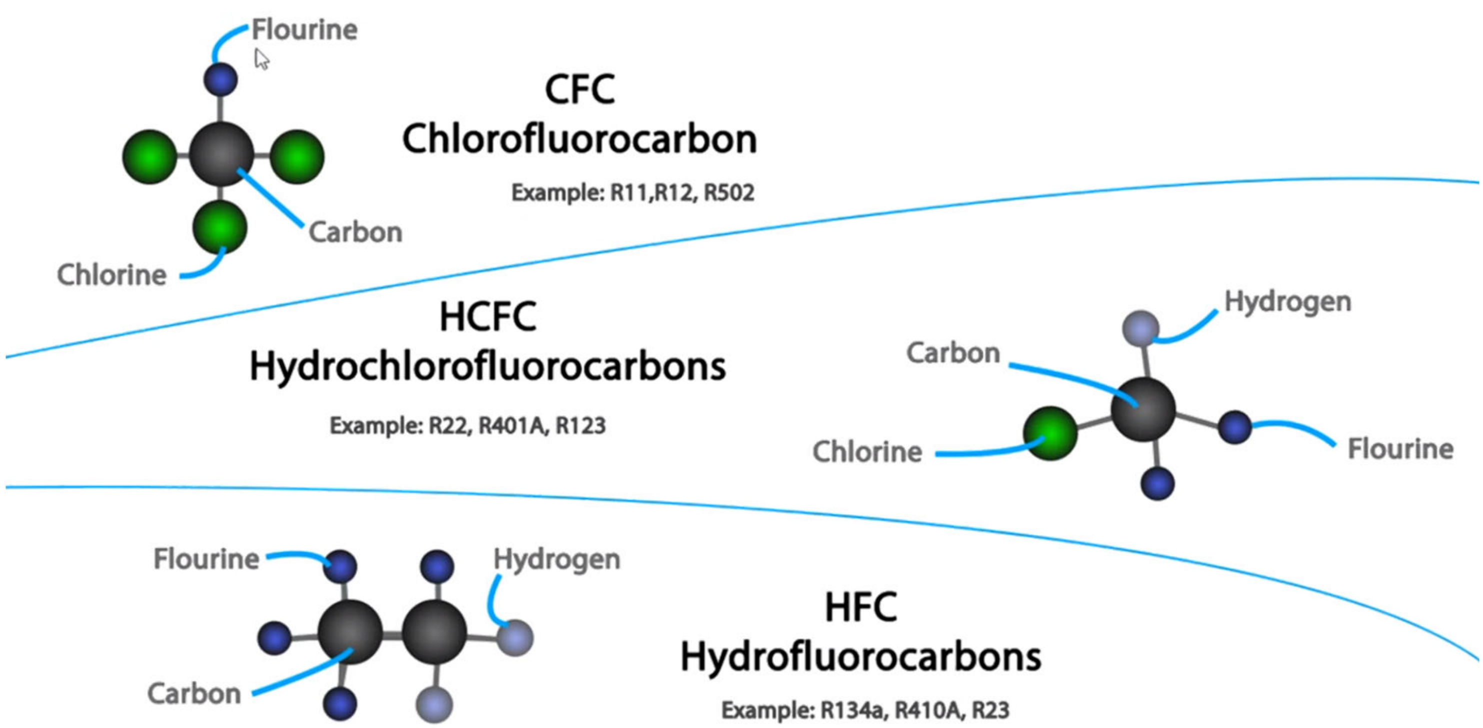
- Miracle substances
- Stable and safe
- NH3
- CFCs and HCFCs
  - R11
  - R12
  - R22
  - R502

3rd Generation ‘Ozone protection’ — 1990 - 2010

- Preserved 2nd gen. features
- Safe and stable
- NH3
- HCFCs and HFCs
  - R134a
  - R410a
  - Blends

4th Generation ‘Global warming’ — 2010 - present

- Fewer choices
- Safety challenges
- NH3
- Natural refrig.
  - CO2
  - Hydrocarbon
- Low GWP HFCs HFOs:
  - R1233zd

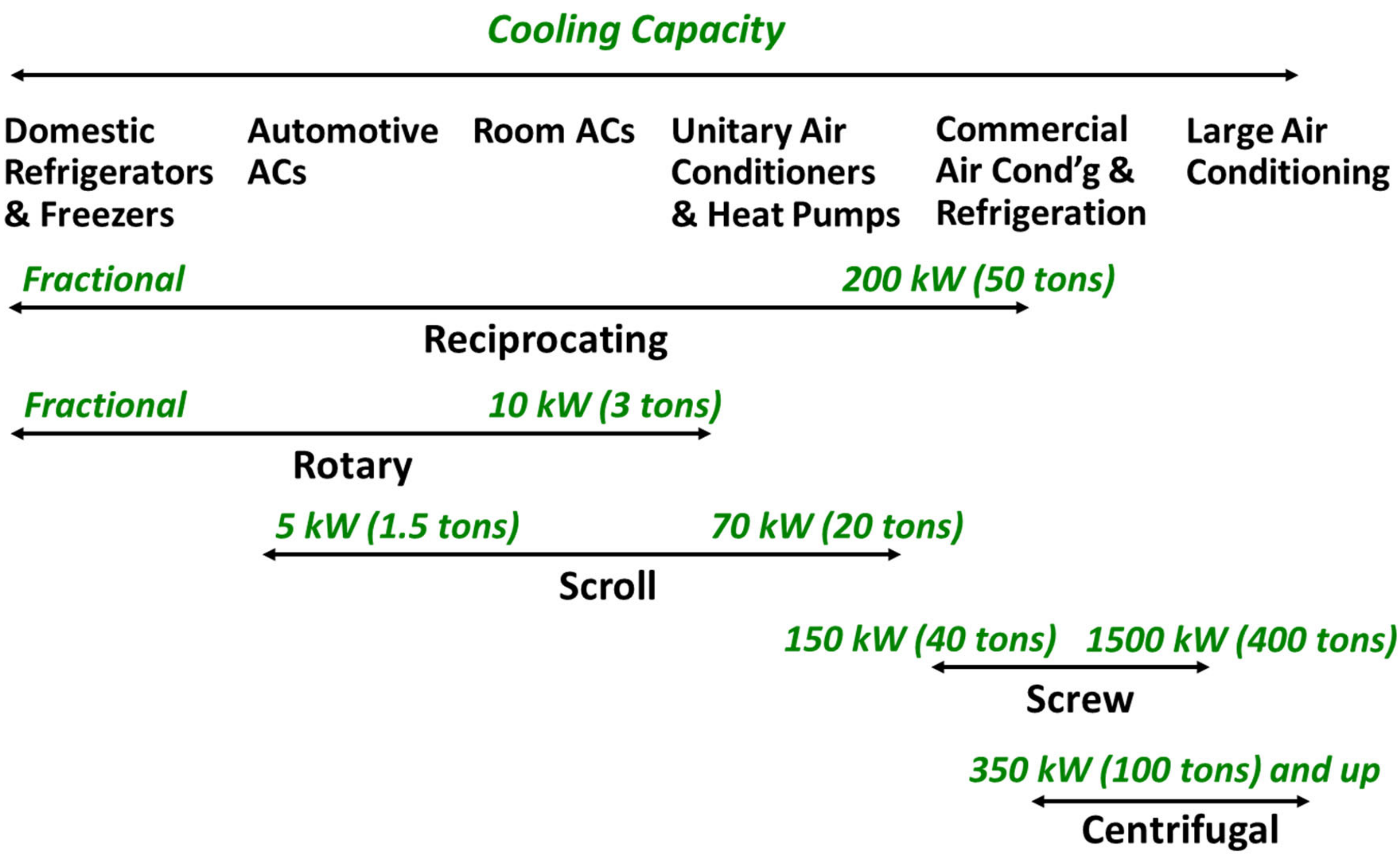


Refrigerant Number	Chemical Formula	NBP °C	Glide K	CT °C	GWP	Safety Group
R-134a	**$CH_2F.CF_3$**	**-26**	**0.0**	**101**	**1300**	**A1**
R-413A	**R-134a/218/600a**	**-35**	**6.9**	**101**	**1770**	**A1/A2**
R-404A	**R-143a/125/134a**	**-47**	**0.7**	**73**	**3260**	**A1/A1**
R-507	**R-143a/125**	**-47**	**0.0**	**71**	**3300**	**A1**
R-407C	**R-32/125/134a**	**-44**	**7.4**	**87**	**1520**	**A1/A1**
R-417A	**R-125/134a/600**	**-43**	**5.6**	**90**	**1950**	**A1/A1**
R-410A	**R-32/125**	**-51**	**0.2**	**72**	**1720**	**A1/A1**
R-508	**R-23/116**	**-86**	**0.0**	**13**	**11860**	**A1**

Refrigerant Number	Chemical Formula	NBP °C	Glide K	CT °C	GWP	Safety Group
R-717	**NH_3**	**-33**	**0.0**	**133**	**0**	**B2**
R-600a	**$CH.(CH_3)_3$**	**-12**	**0.0**	**135**	**3**	**A3**
R-290	**C_3H_8**	**-42**	**0.0**	**97**	**3**	**A3**
R-1270	**C_3H_6**	**-48**	**0.0**	**92**	**3**	**A3**
R-744	**CO_2**	**-57**	**0.0**	**31**	**1**	**A1**

Compressors

Range of capacity applications for compressor types



Compressor Configurations

Hermetic:

- Welded steel shell houses both compressor and motor
- Usually smaller sizes; high manufacturing cost of larger sizes

Semi-hermetic:

- Common, but bolted, housing for compressor & motor
- Intermediate capacities
- Often multiple cylinders for increased capacity

Open Drive:

- Motor external to shell
- Largest capacities
- Shaft seal necessary

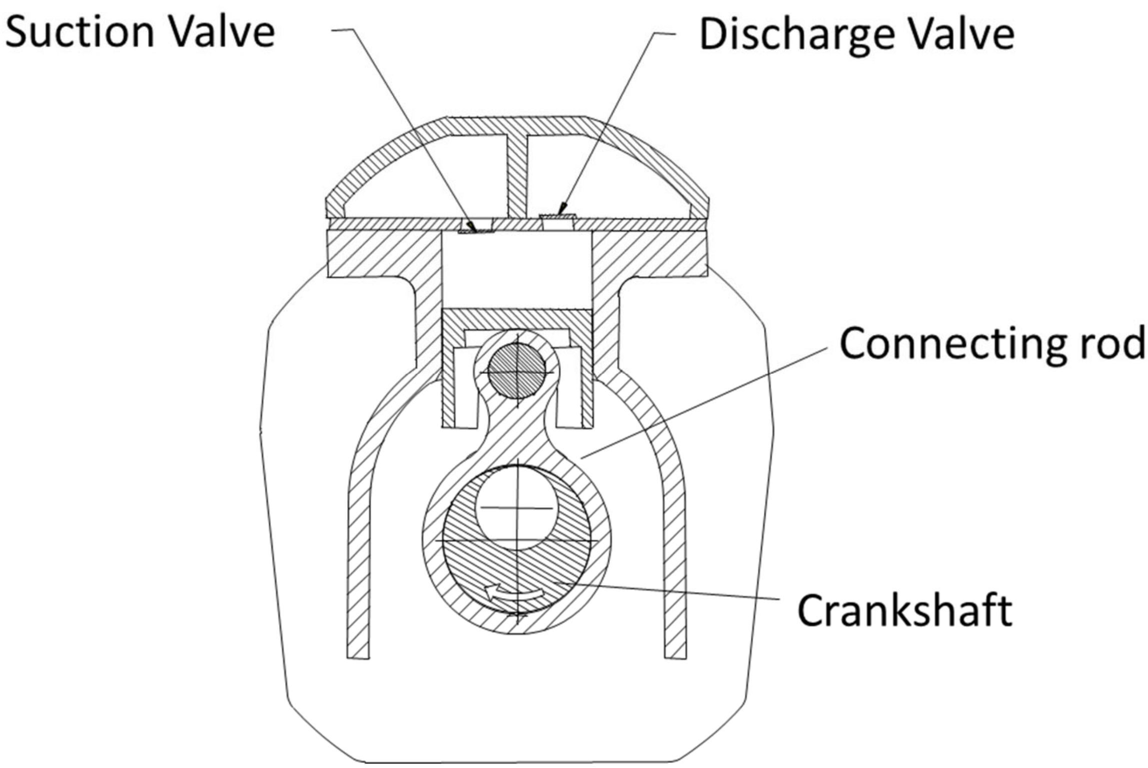
Hermetic

Semi-hermetic

Open-type

Reciprocating Compressor

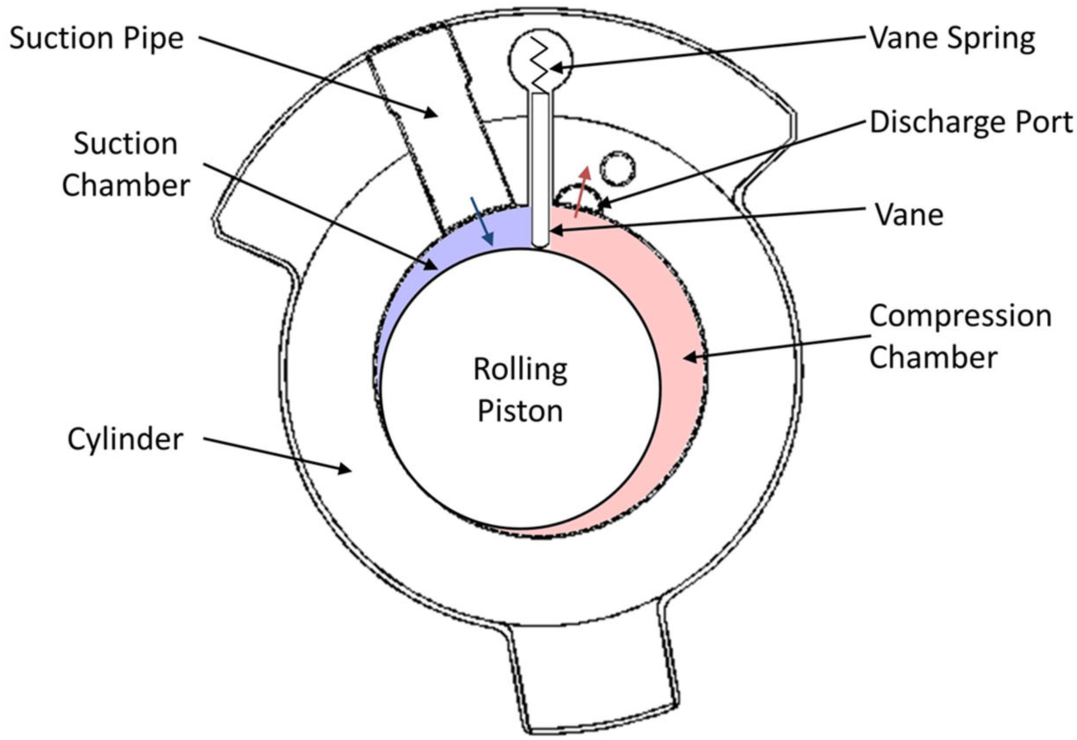
- Widely used; simple to make and low cost
- Parallel compressors are low-cost way to obtain multiple capacities and improved part load efficiency



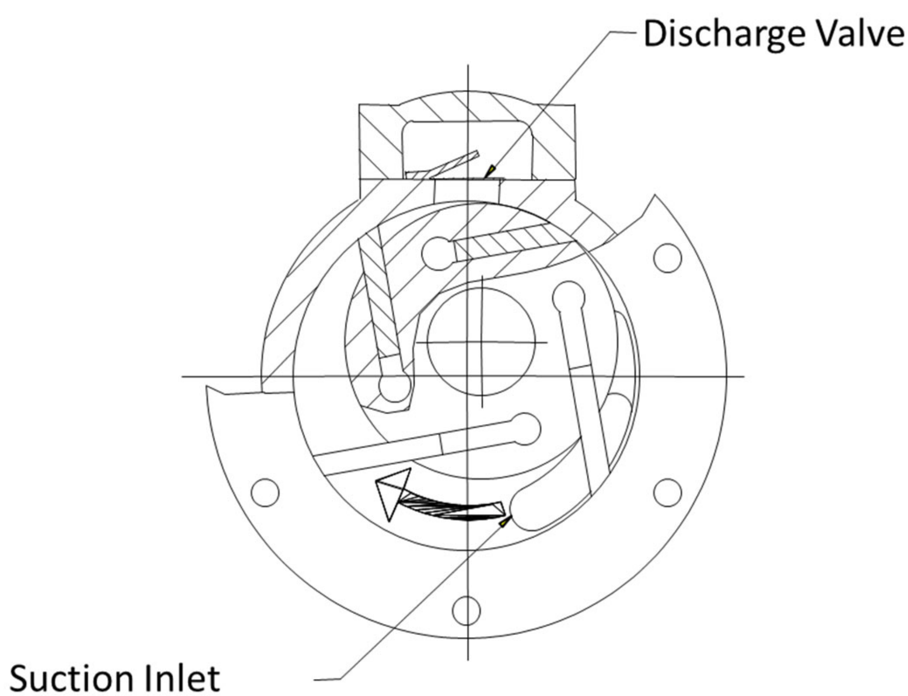
Rotary Compressor

- Two types: stationary vane (also called rolling piston) and sliding vane compressor
- Smaller size for given capacity then reciprocating
- Better reliability and operation over larger speed range

Rolling piston

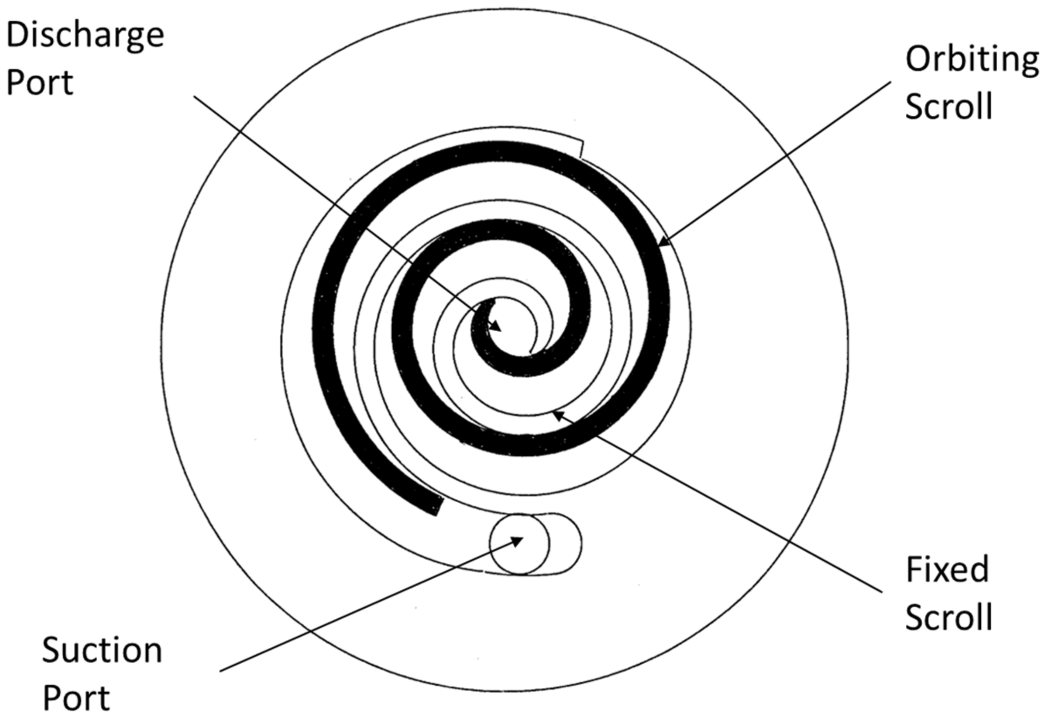


Sliding vane



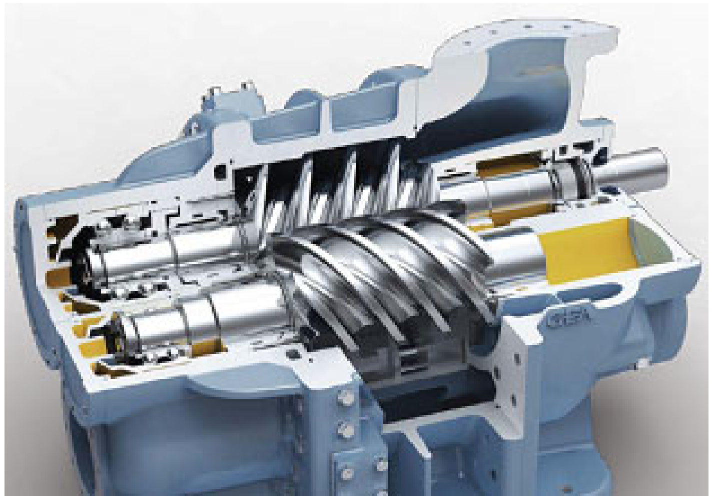
Scroll Compressor

- Relatively complicated orbiting mechanism
- No valves, better reliability
- Ideal for variable speed and capacity
- Better dynamic balance, more uniform shaft torque, less pressure oscillations, etc



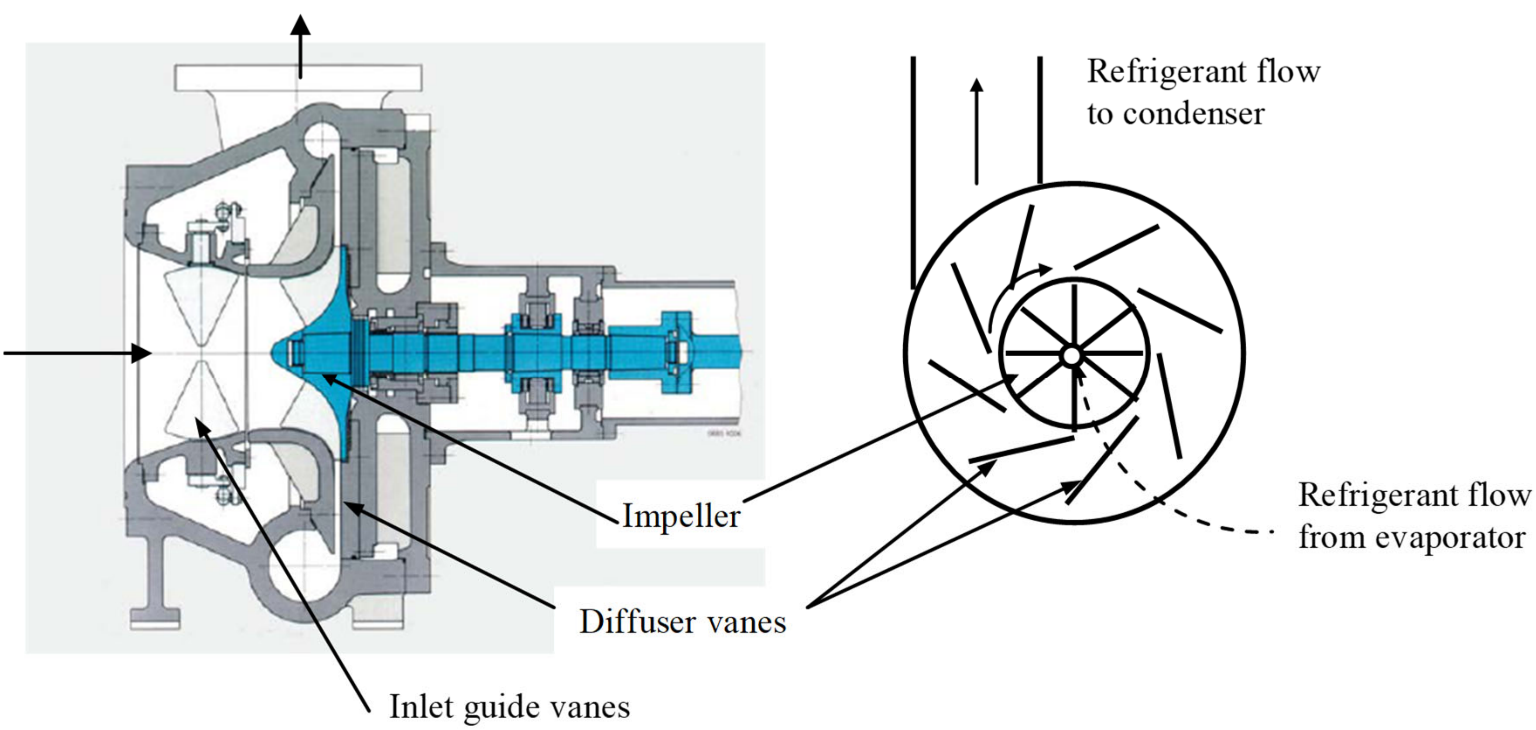
Screw Compressor

- Better efficiency
- Works well with speed and capacity control
- Commonly used in the 30-100 ton range

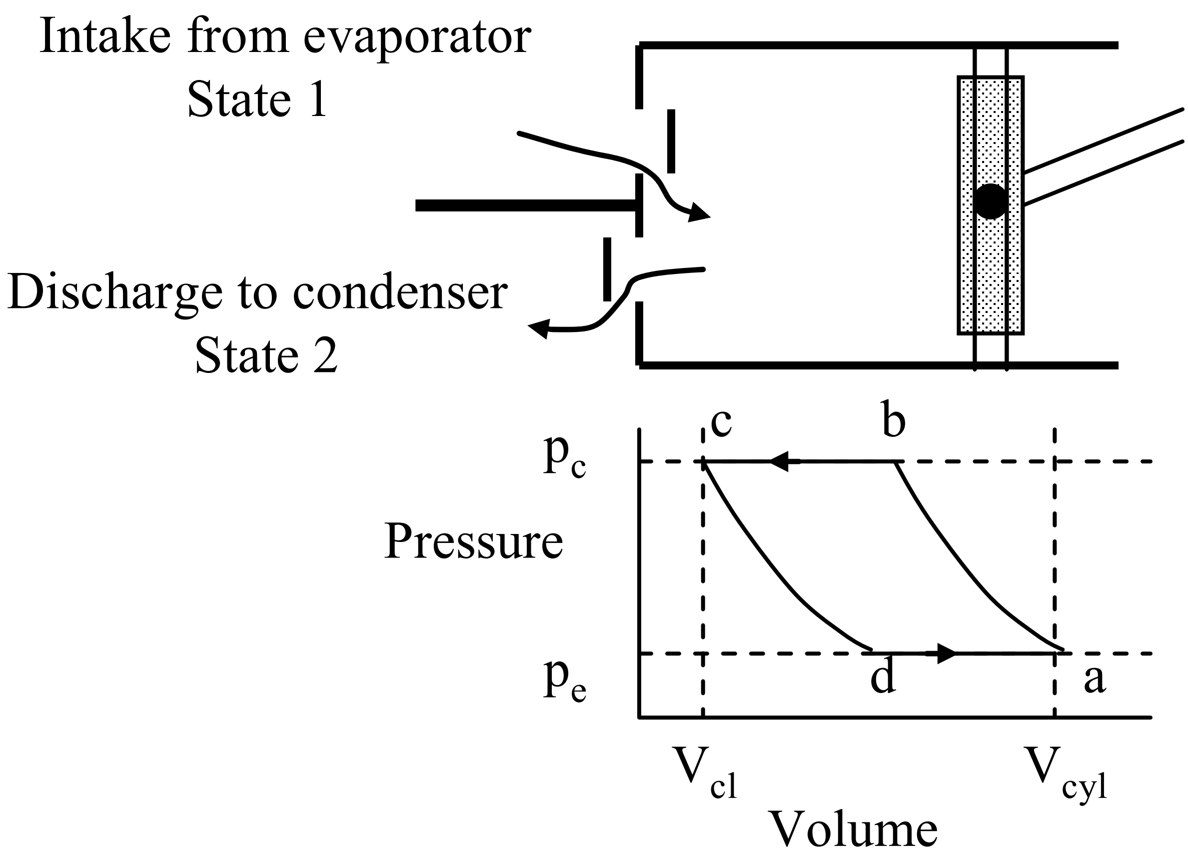


Centrifugal Compressor

- High rotational speed and refrigerant flow
- Economically viable for sizes > 100 tons
- Capacity control through variable speed or inlet guide vane angle control



Performance Analysis of Reciprocating Compressor



Refrigerant mass flow rate

$$\dot{m} = \dot{N}\frac{(V_a - V_d)}{v_s}$$

Displacement volume

$$V_{disp} = (V_a - V_c)$$

Clearance volume fraction

$$C = \frac{V_c}{\left(V_a - V_c\right)}$$

Volumetric efficiency

$$\eta_v = \frac{\text{Volume flow rate}}{\text{Displacement rate}}$$

$$\Downarrow$$

$$\eta_V = \frac{\dot{N}\left(V_a - V_d\right)}{\dot{N}\left(V_a - V_c\right)} = \frac{\left(V_a - V_d\right)}{\left(V_a - V_c\right)}$$

$$\Downarrow$$

$$\eta_{v,c} = 1 + C - C\left(\frac{V_d}{V_c}\right)$$

Assuming compression process is polytropic, i.e.,

$$p\, v^n = \text{constant}$$

$$\Downarrow$$

$$p_a\, v_a^n = p_b\, v_b^n \text{ and } p_c\, v_c^n = p_d\, v_d^n$$

Then volume ratio is

$$\left(\frac{V_d}{V_c}\right) = \left(\frac{v_d}{v_c}\right) = \left(\frac{p_c}{p_d}\right)^{1/n} = \left(\frac{p_c}{p_e}\right)^{1/n}$$

Volumetric efficiency can be rewritten as

$$\eta_{v,c} = 1 + C - C\left(\frac{p_c}{p_e}\right)^{1/n}$$

Refrigerant mass flow rate

$$\dot{m} = \eta_v \frac{\dot{N}\, V_{disp}}{v_s}$$

⇩

$$\dot{m} = \left[1 + C - C\left(\frac{p_c}{p_e}\right)^{1/n} \right] \frac{\dot{N}\, V_{disp}}{v_s}$$

Compressor power is

$$\dot{W}_c = \dot{m}\left[\int_a^b p\, dv - \int_d^c p\, dv\right]$$

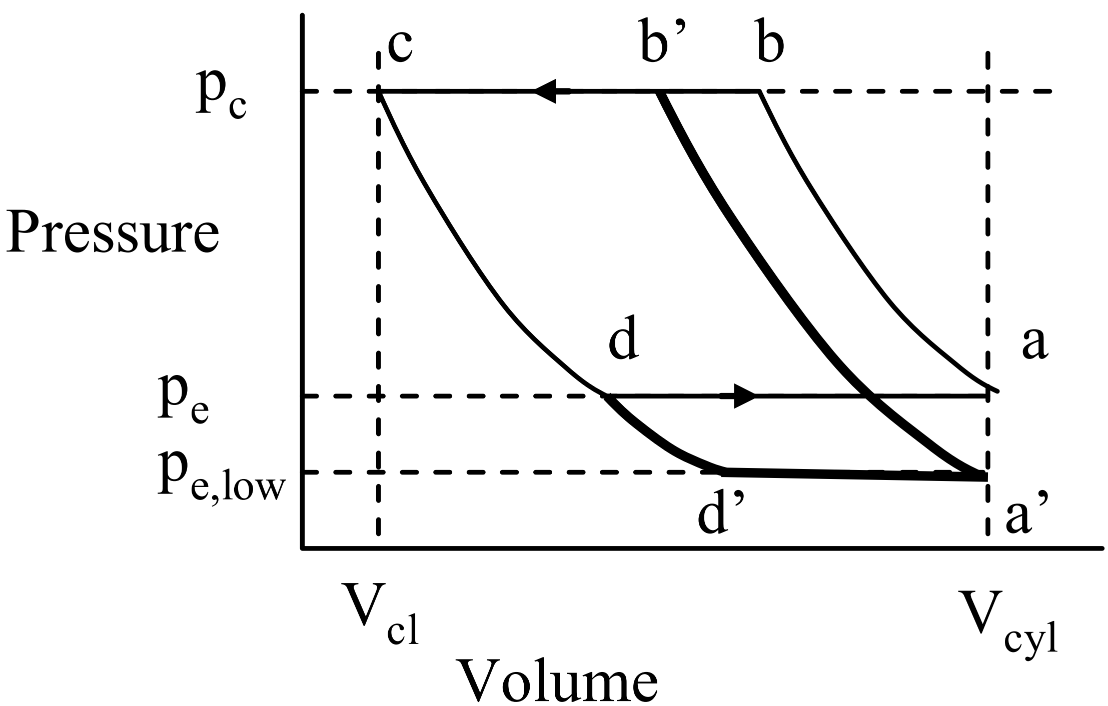
$$\dot{W}_c = \dot{N}\left(\frac{n}{n-1}\right)\eta_V\, p_e\, V_{disp}\left[\left(\frac{p_c}{p_e}\right)^{\frac{n}{n-1}} - 1\right]$$

Compressor efficiency is defined as

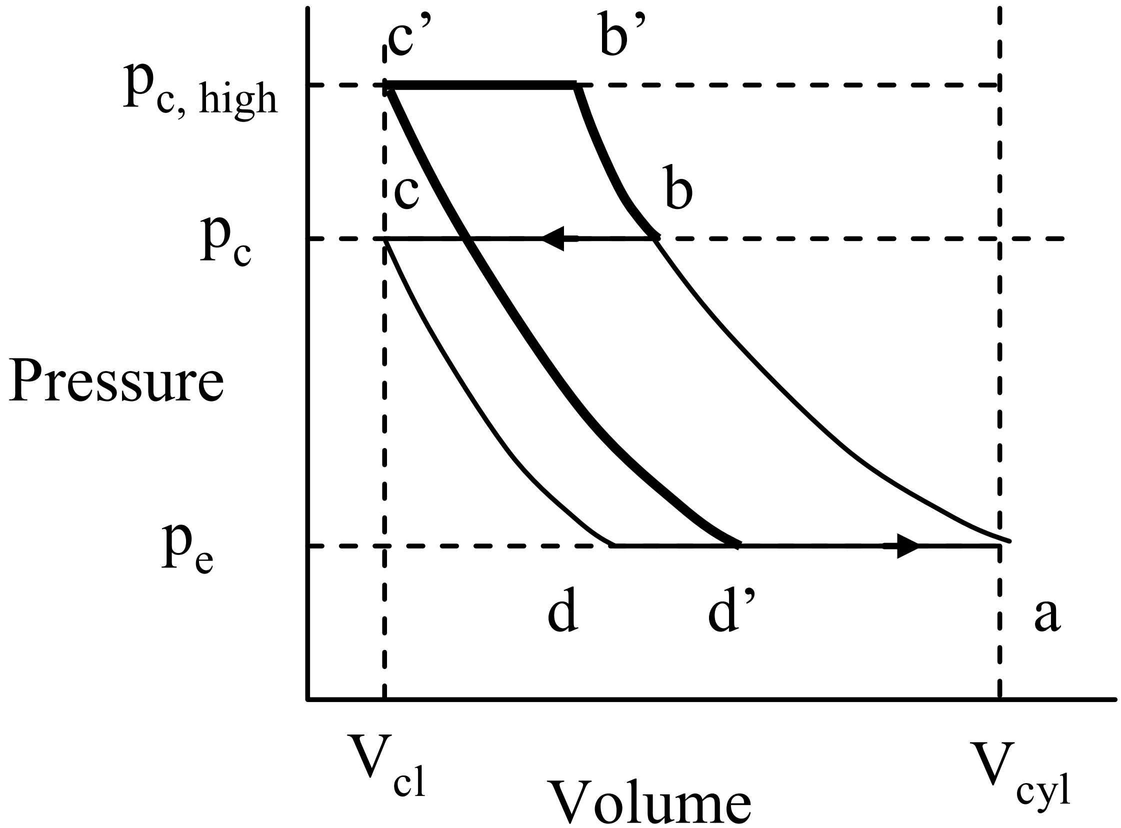
$$\eta_c = \frac{\dot{W}_c}{\dot{W}_{elec}}$$

Compressor Example: Determine the clearance volumetric efficiency, mass flow rate, reversible polytropic power requirement (kW), cooling capacity (tons), and coefficient of performance for a refrigeration system with a reciprocating compressor that has a displacement volume of 0.02 ft3, a clearance volume fraction of 0.05, a rotational speed of 1740 rpm. The refrigerant is R-22, and leaves the evaporator at a saturation pressure corresponding to 25 F with 5 F superheat and leaves the condenser as saturated liquid at 120 F. The polytropic exponent for the process is 1.2.

Pressure-Volume Diagram for Different Evaporator Pressure



Pressure-Volume Diagram for Different Condenser Pressure



<u>Compressor Pressure Effect Example</u>: Determine and plot the effects of condenser and evaporator pressure on the clearance volumetric efficiency, mass flow rate, capacity and power for the ideal system of the previous example.

Performance Correlations for Positive Displacement Compressors (ANSI/ARI Standard 540)

$$F = c_1 + c_2 T_s + c_3 T_d + c_4 T_s^2 + c_5 T_s T_d + c_6 T_d^2 + c_7 T_s^3 + c_8 T_d T_s^2 + c_9 T_s T_d^2 + c_{10} T_d^3$$

Isentropic efficiency as a function of suction and discharge dewpoint temperatures

Discharge dewpoint T_d (F)	Suction dewpoint temperature T_s (F)								
	-10	0	10	20	30	40	45	50	55
150						0.585	0.610	0.632	0.651
140					0.570	0.625	0.648	0.666	0.681
130				0.552	0.613	0.662	0.680	0.695	0.704
120			0.531	0.597	0.652	0.692	0.705	0.714	0.716
110		0.507	0.577	0.636	0.682	0.711	0.718	0.718	0.712
100	0.481	0.554	0.616	0.666	0.700	0.714	0.711	0.701	0.683
90	0.527	0.591	0.643	0.680	0.698	0.692	0.677	0.654	0.620
80	0.563	0.614	0.653	0.674	0.672	0.640	0.610	0.569	0.515