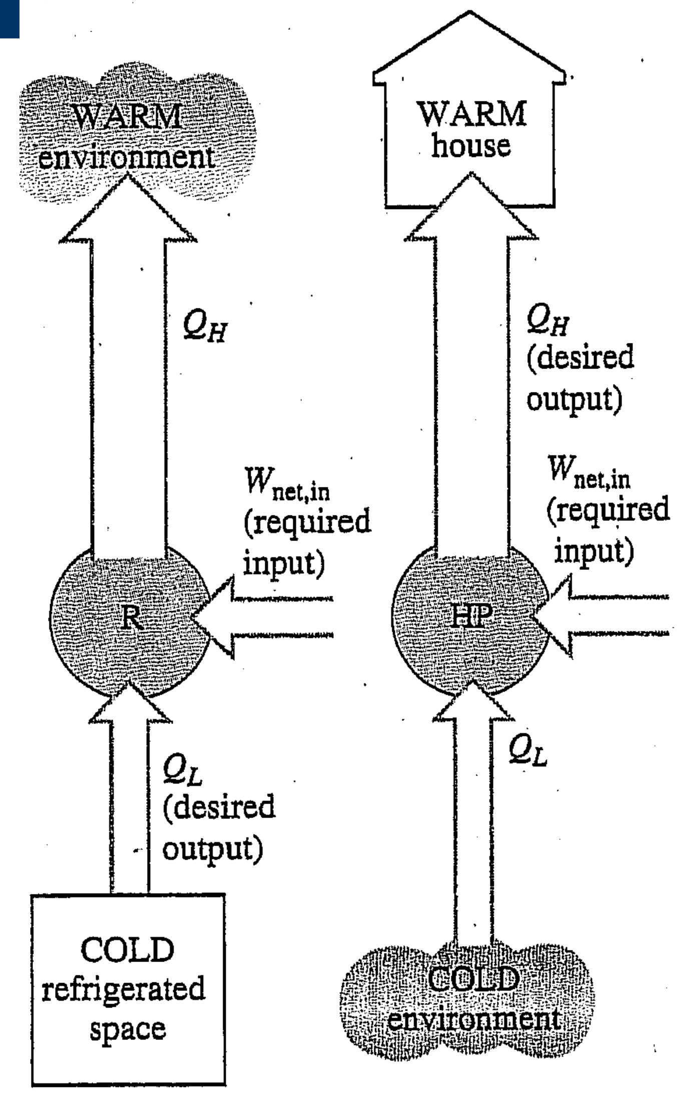
Refrigeration Systems

COP

- COP = coefficient of performance
- Air conditioners, refrigerators: $COP=Q_L/W_{net}$
- Heat pumps: $COP=Q_H/W_{net}$
- Energy balance: $W_{net}+Q_L=Q_H$



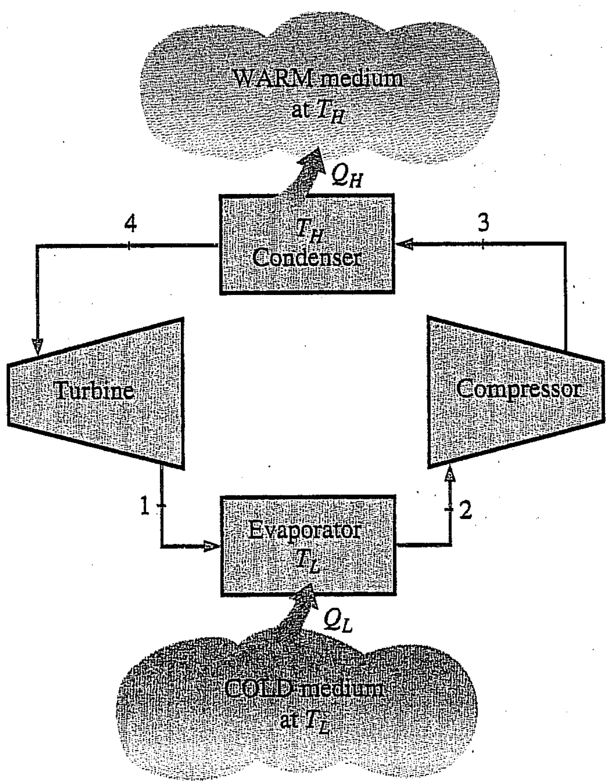
(*a*) Refrigerator (*b*) Heat pump

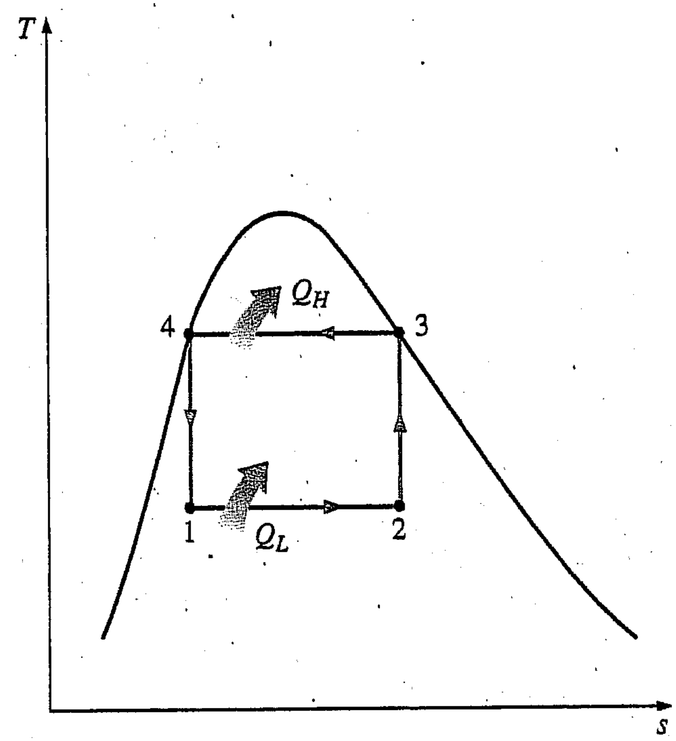
From Cengel, Thermodynamics: An Engineering Approach, 6th ed.

Reversed Carnot cycle -- ideal

$$COP_{R,Carnot} = \frac{1}{T_H/T_L - 1}$$

$$COP_{HP,Carnot} = \frac{1}{1 - T_L/T_H}$$



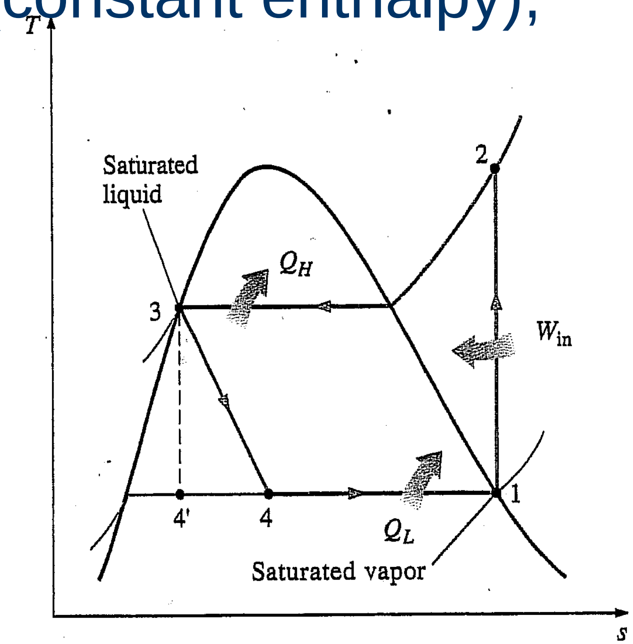


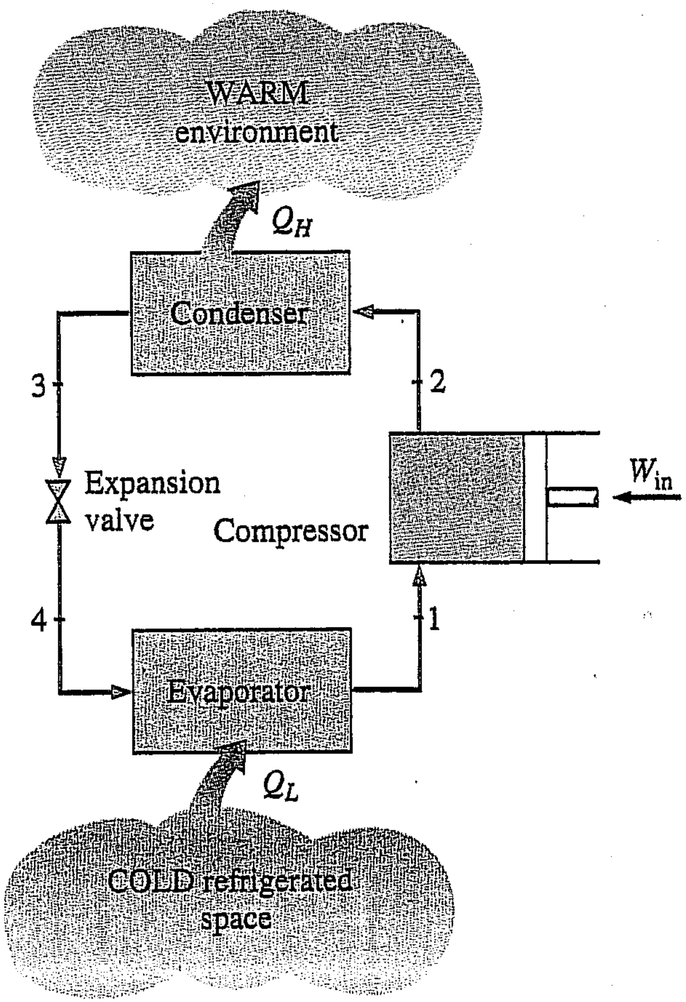
Why isn't this cycle possible in real life?

From Cengel, Thermodynamics: An Engineering Approach, 6th ed.

Ideal Refrigeration Cycle

1) x=1 (saturated vapor), $P=P_{low}$ or $T=T_{low}$
2) $P=P_{high}$, $s_2=s_1$ (constant entropy)
3) $P=P_{high}$, x=0 (saturated liquid)
4) $h_3=h_4$ (constant enthalpy), $P=P_{low}$





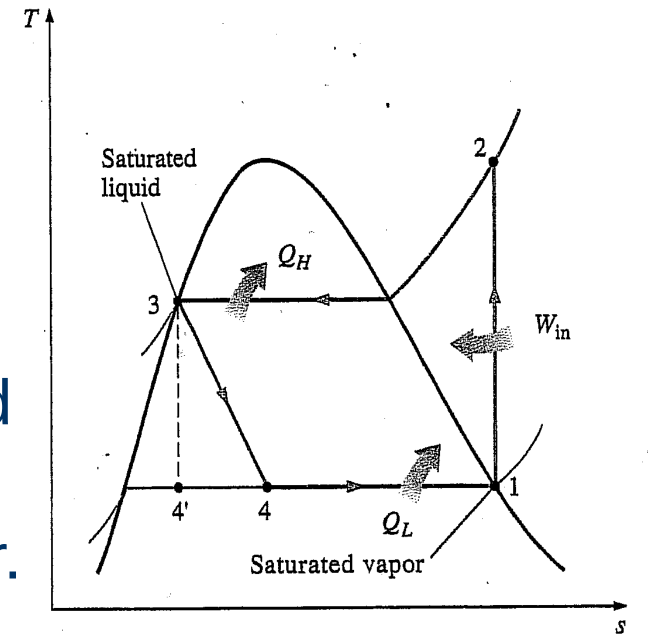
From Cengel, Thermodynamics: An Engineering Approach, 6th ed.

Example

- An ideal vapor-compression cycle has a mass flow rate of R-134a of 0.05 kg/s. The low and high system pressures are 0.12 MPa and 0.70 MPa. Find
  - The rate of power input
  - The rate of heat transfer out of the refrigerated space
  - The rate of heat transfer to the surroundings
  - COP

Cycle efficiency

- To increase the COP of the cycle, increase the evaporation temperature or decrease the condensing temperature.
  - However, you can't achieve as cold of a temperature now, and your heat exchanger will need to be larger since ΔT is smaller.
  - 2-4% increase in COP per degree temperature change



Sources of Inefficiencies

- *Compressor efficiency < 100%
- Pressure drop in piping
- Heat transfer to/from lines
- *Superheating of fluid entering compressor to prevent liquid from entering
- *Subcooling of fluid entering expansion valve to prevent vapor from entering

* We will only look at these in class.

Expansion Valve Operation

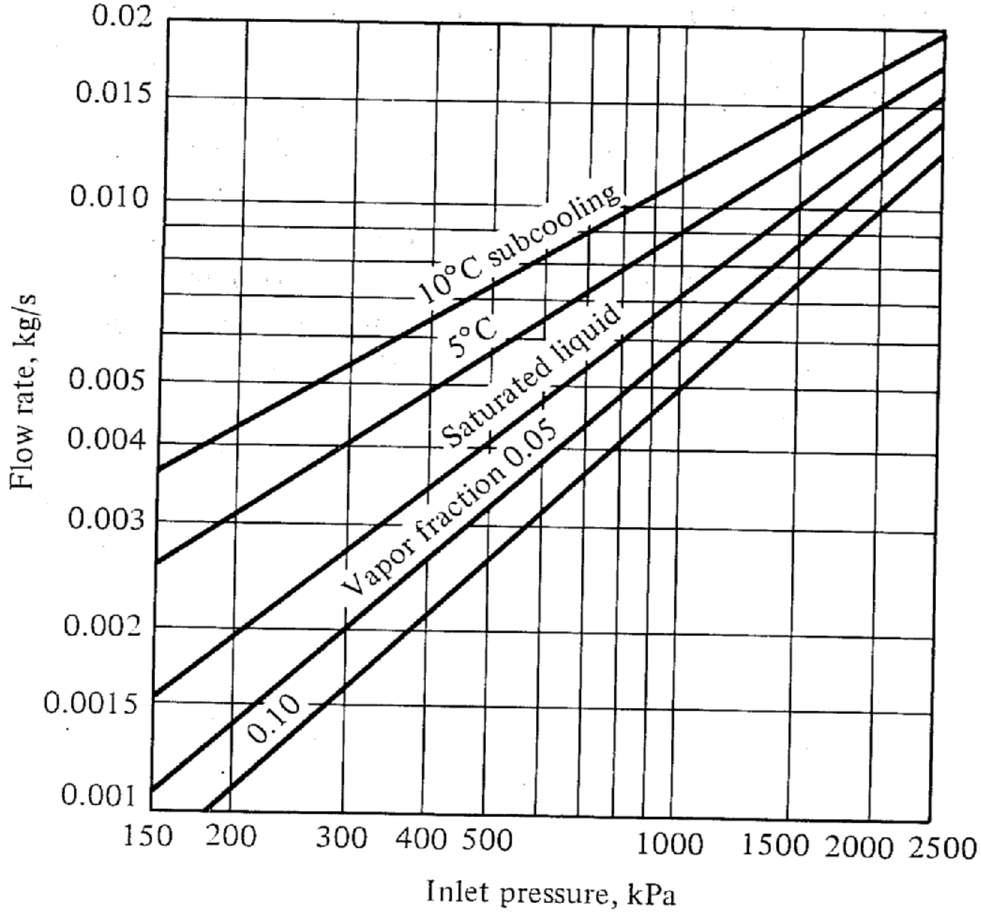


Figure 13-7 Flow rate of refrigerant 12 or 22 through a capillary tube 1.63 mm in diameter and 2.03 m long under choked-flow conditions.

Stoecker and Jones, Refrigeration and Air Conditioning, 2nd ed, Mc-Graw Hill.

Example

- A vapor-compression refrigeration cycle operates using R-134a with low and high system pressures of 0.10 MPa and 1.20 MPa. The fluid leaves the evaporator superheated by 6.37°C and leaves the condenser subcooled by 4.29°C. Calculate the COP if the compressor efficiency is a) 100% and b) 84%.

Compressor Performance

Compressor Basics

- As with ideal pumps, dh=vdP. However, v is not a constant, making calculation of h_2-h_1 more complicated.
- For a polytropic process, Pv^n=C

$$h_2 - h_1 = \int_1^2 v\,dP = \int_1^2 \left(\frac{C}{p} \right)^{1/n} dP \qquad (1)$$

- For an isentropic process and an ideal gas, n=k (where k=c_p/c_v), and for an isothermal process, n=1.

Compressor Efficiency

- The adiabatic compressor efficiency:

$$\eta_a = {W_{isentropic}}\Big/{W_{actual}} = {\left(h_2 - h_1\right)_s}\Big/{\left(h_2 - h_1\right)_{actual}} \qquad (2)$$

- Total compressor efficiency:

$$\eta_{compressor} = \eta_a \eta_{motor\ drive} \eta_{mechanical} \qquad (3)$$

- Typical efficiencies are 90% for the motor drive at peak load, 90% for the mechanical efficiency, and 76% to 97% for the adiabatic (isentropic) efficiency.
- Typically, as the compressor size increases, so does the adiabatic efficiency.

Exit temperature

- A maximum recommended fluid temperature is given based on compressor and fluid type.
- Air compressors typically shouldn't have an air exit temperature greater than 300-375ºF to prevent carbonizing, combustion of oil vapor, or weakening of parts over time.
- Air can be modeled as a perfect gas where

$$Pv = RT/M \quad \text{and} \quad c_p - c_v = R/M$$

- These can be substituted into Equ. (1), and using Equ. (2) or (3) as well, the exit air temperature T_2 can be found as a function of pressure ratio r, n, k, and efficiency.
- Once T_2 is known, the compressor work can be found using

$$W_{actual} = h_2 - h_1 = \dot{m} c_p \left(T_2 - T_1 \right)$$

Decreasing Compressor Work

- Two possible methods
  - Minimize irreversibilities due to friction, turbulence, and non-quasi-equilibrium compression
  - Make the specific volume of the gas as low as possible by cooling the compressor since in the ideal case

$$W_{compressor} = h_2 - h_1 = \int_1^2 v dP$$

- One cooling possibility

is to use multi-stage compression with intercooling.

From Cengel, Thermodynamics: An Engineering Approach, 4th ed.

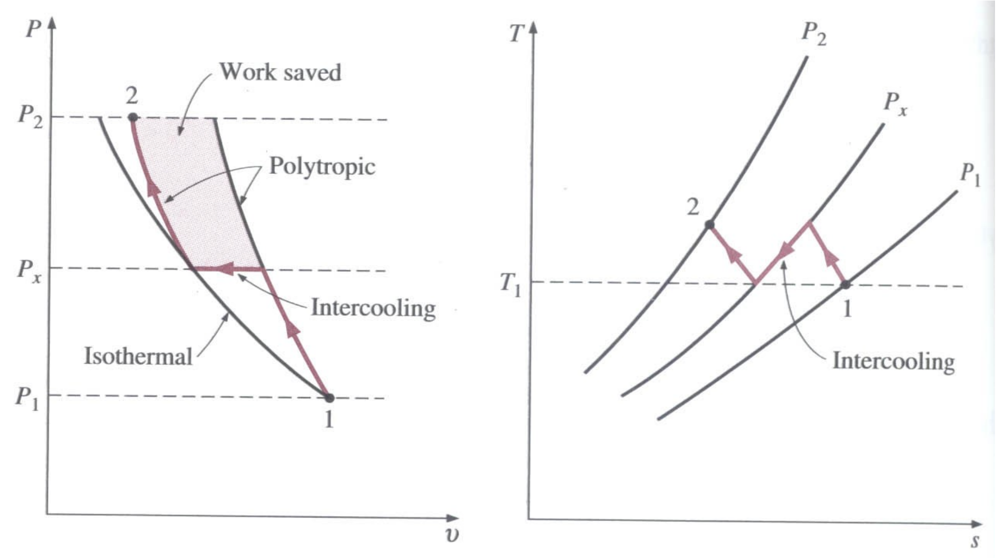
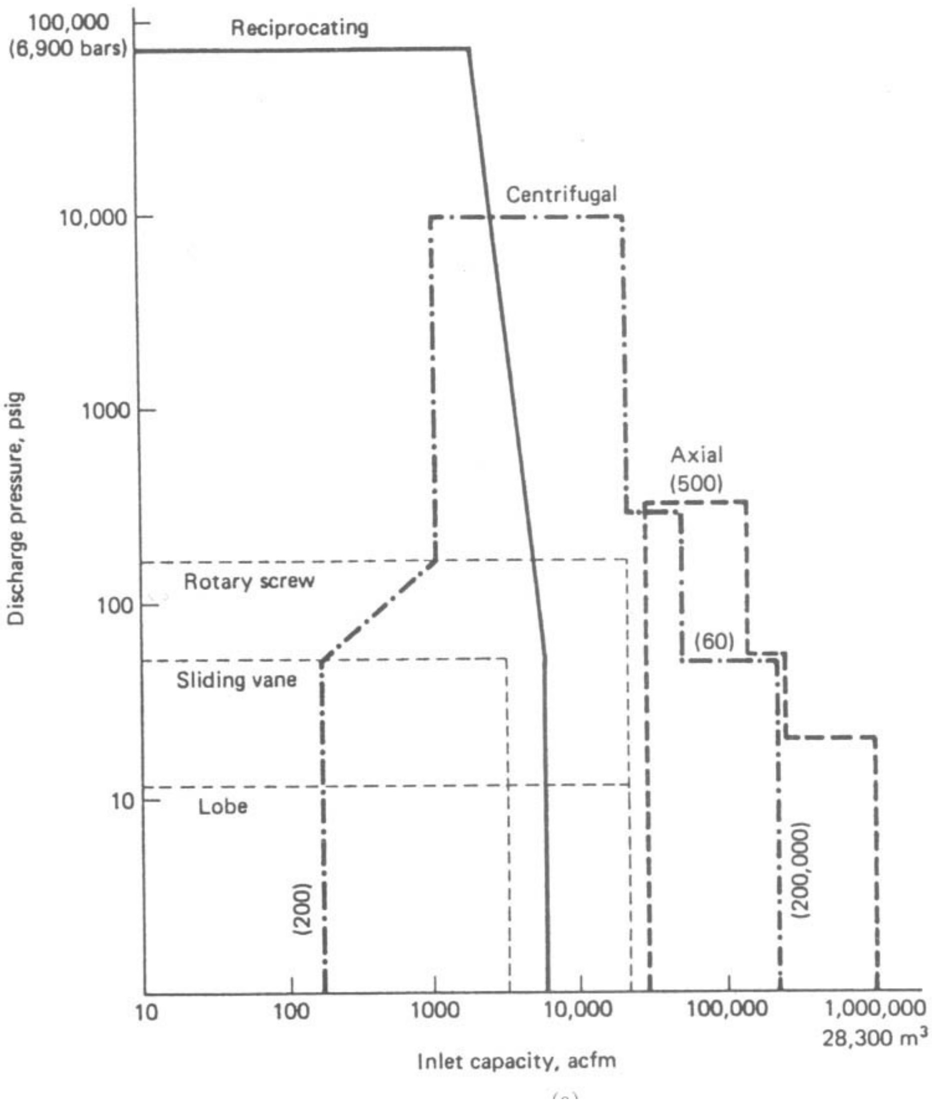


FIGURE 6–46
P-v and T-s diagrams for a two-stage steady-flow compression process.

Compressor Types

- Five most common types
  - Reciprocating
    - Uses a piston-cylinder and valves
    - Most common type of compressor
  - Screw
    - Lobes of two rotating screws trap and compress gas
  - Centrifugal
    - Uses centrifugal force to compress gas
    - Common in large refrigeration systems (200 to 10000 kW of refrigeration capacity)
  - Vane
    - Uses a roller to compress gas
    - Used in most domestic refrigeration and ac systems
  - Scroll
    - Two inter-fitting spiral-shaped scrolls compress the gas
    - Used in 1-15 ton (3.5 to 53 kW) range AC applications

Compressor pressure ranges

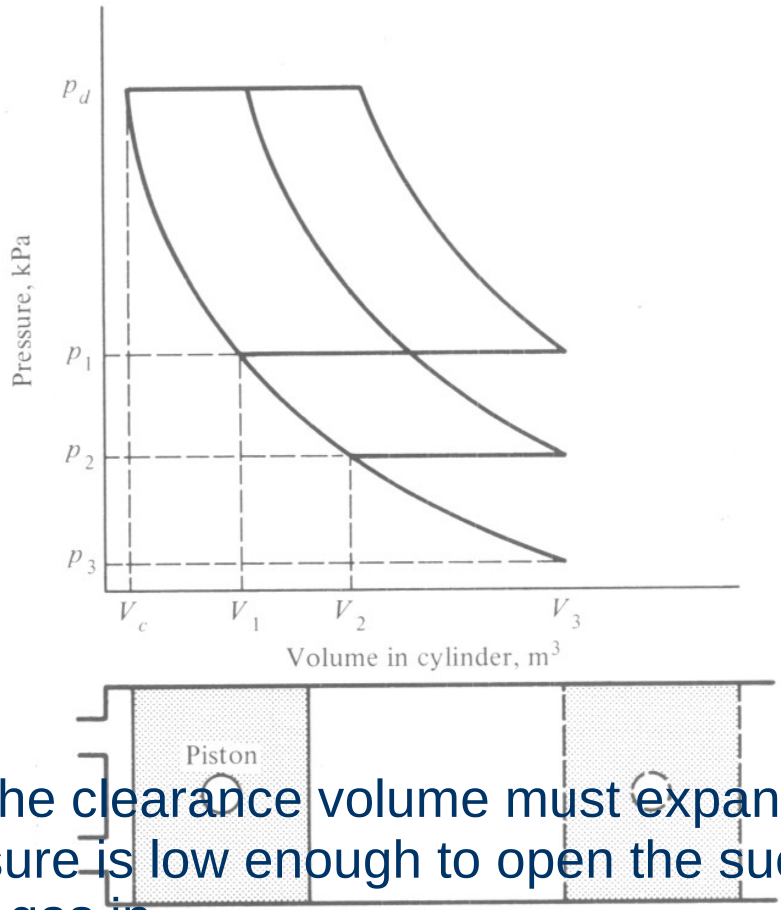


From Burmeister, Elements of Thermal-Fluid Design.

Terminology

- Open-type compressor
  - Crankshaft extends through housing to connect with the motor
  - Seals are used to limit leakage
- Hermetically sealed
  - Motor and compressor are combined in the same housing
  - Used for small domestic air conditioning systems
- Semi-hermetic
  - Cylinder heads are removable for serviceability. Good for AC systems larger than domestic.
- Condensing unit
  - Motor, compressor, and condenser are combined in one unit and sold together

Reciprocating Compressors



Gas in the clearance volume must expand to V_1 before the pressure is low enough to open the suction valves and draw more gas in.

Stoecker and Jones, Refrigeration and Air Conditioning, 2nd ed, Mc-Graw Hill.

Reciprocating Compressors, cont.

- Actual volumetric efficiency

$$\eta_{va} = \frac{\text{volume flow rate entering compressor} \left({}^{\text{m}^3}\!/\!_{\text{s}} \right)}{\text{displacement rate of compressor} \left({}^{\text{m}^3}\!/\!_{\text{s}} \right)} x100$$

- Clearance volumetric efficiency

$$\eta_{va} = \frac{\text{volume of gas drawn into cylinder}}{\text{useable volume of cylinder}} x100 = \frac{V_3 - V_1}{V_3 - V_c} x100$$

  - The clearance volumetric efficiency tells us what percent of the clearance volume is used to bring new gas in.

- Percent clearance

$$m = \frac{V_c}{V_3 - V_c} x100$$

Reciprocating Compressors, cont.

- After some algebra

$$\eta_{vc} = 100 - m\left(\frac{V_1}{V_c} - 1\right)$$

where

$$\frac{V_1}{V_c} = \frac{v_{suc}}{v_{dis}}$$

v_{suc}=specific volume of vapor entering compressor

v_{dis}=specific volume of vapor after isentropic compression

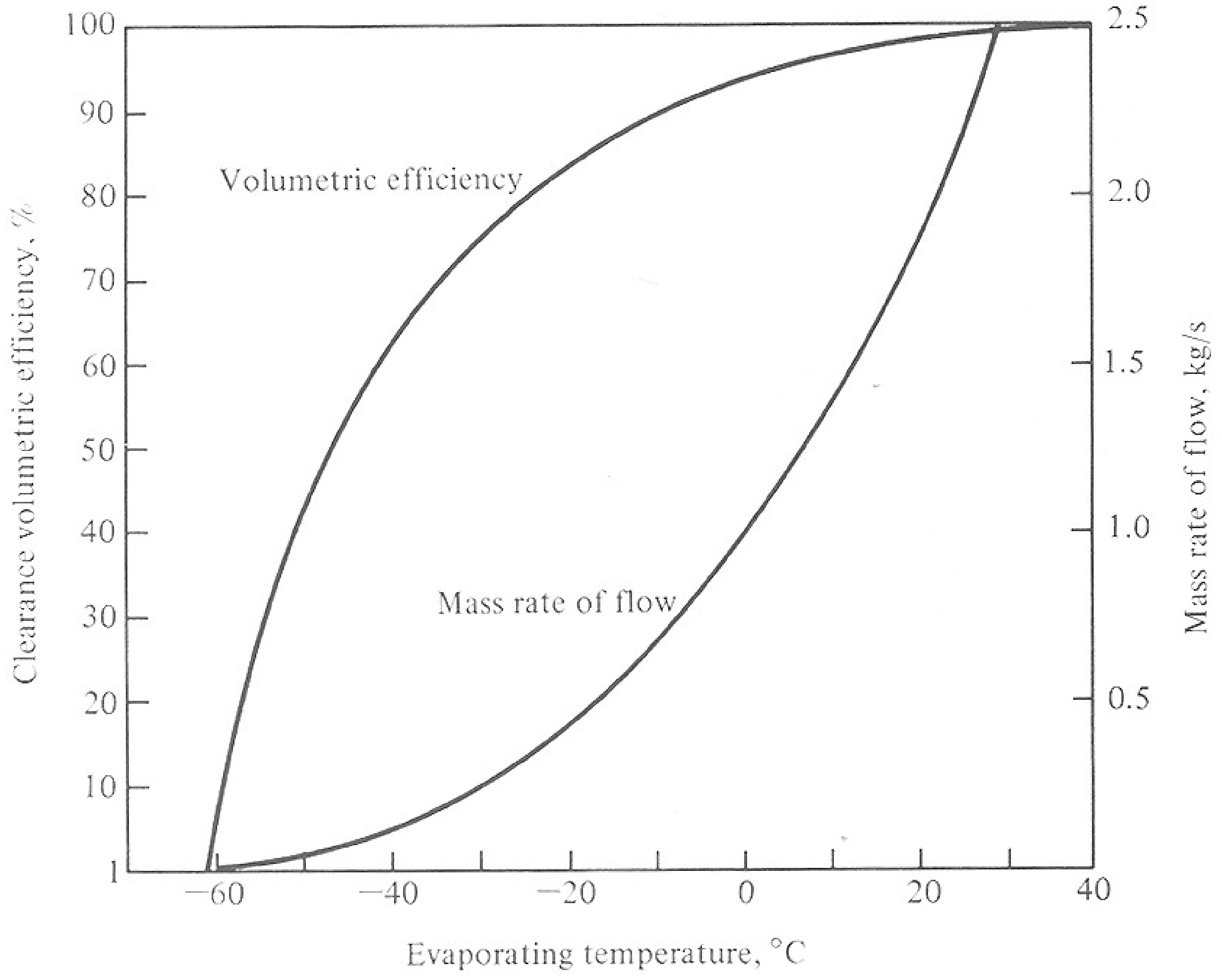
Reciprocating Compressors, cont.

- To find mass flow rate (kg/s)

$$\dot{m} = \text{displacement rate x } \frac{\eta_{\text{vc}}/100}{v_{suc}}$$

- The displacement rate is a volumetric flow rate; v_{suc} converts that to a mass flow rate
- As the suction pressure (and evaporating temperature) drops, what happens to the mass flow rate?
- On a cold winter day, the evaporating temperature will be very low for a room AC unit. What problems could this cause?

Reciprocating Compressor Performance



Stoecker and Jones, Refrigeration and Air Conditioning, 2nd ed, Mc-Graw Hill.

Reciprocating Compressor Performance

- Most refrigeration systems operate on the left side of the power curve.
- During startup, the power requirement may pass the peak and demand more motor power.

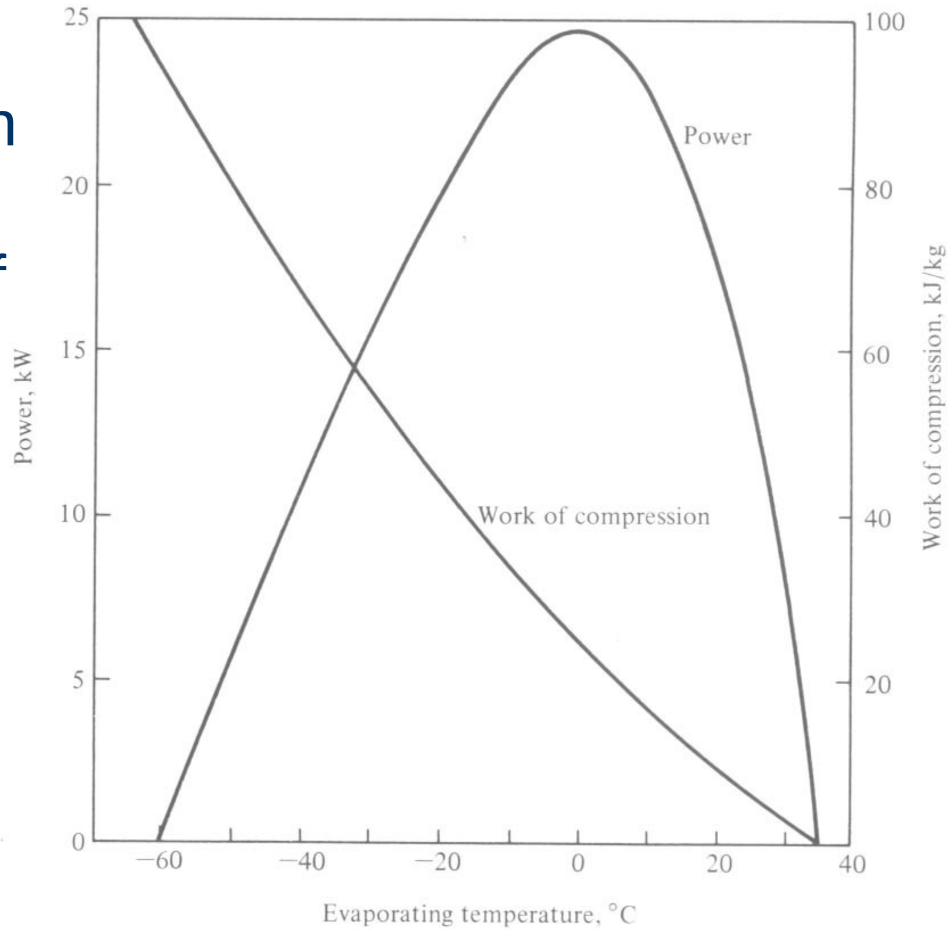


Figure 11-6 Work of compression and power required by an ideal compressor, Refrigerant 22, 4.5 percent clearance, 50 L/s displacement rate, and 35°C condensing temperature.

Stoecker and Jones, <u>Refrigeration and Air Conditioning</u>, 2nd ed, Mc-Graw Hill.

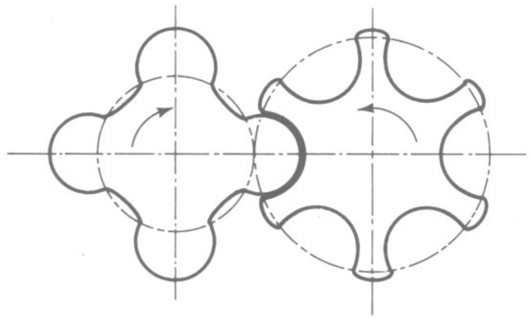
Reciprocating Compressors, cont.

- Adiabatic compression (isentropic) efficiency (use this to find the actual enthalpy at the compressor exit)

$$\eta_a = \frac{w_{isentropic}}{w_{actual}} x100$$

- Losses are due mainly to friction of rubbing surfaces and pressure drop across valves
- Watch your exit conditions. If the exit temperature is too hot, the oil will break down and reduce the life of your valves. The maximum recommended oil temperature varies with the oil type.
- This can be a problem especially with ammonia, which tends to have high discharge temperatures. Ammonia compressors often are equipped with external water cooling.

Rotary Screw Compressors



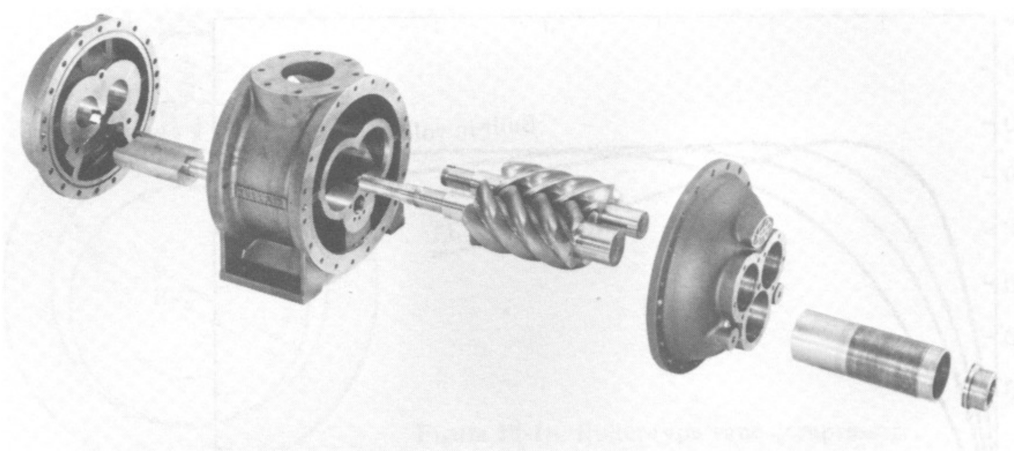
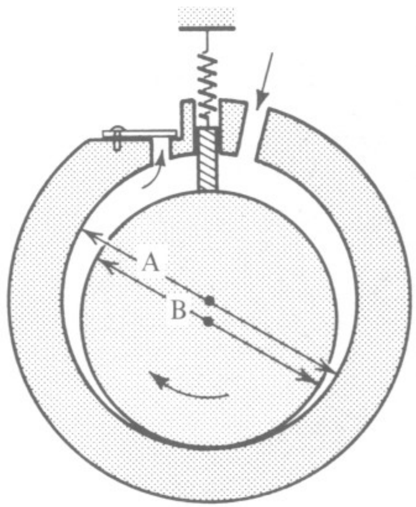


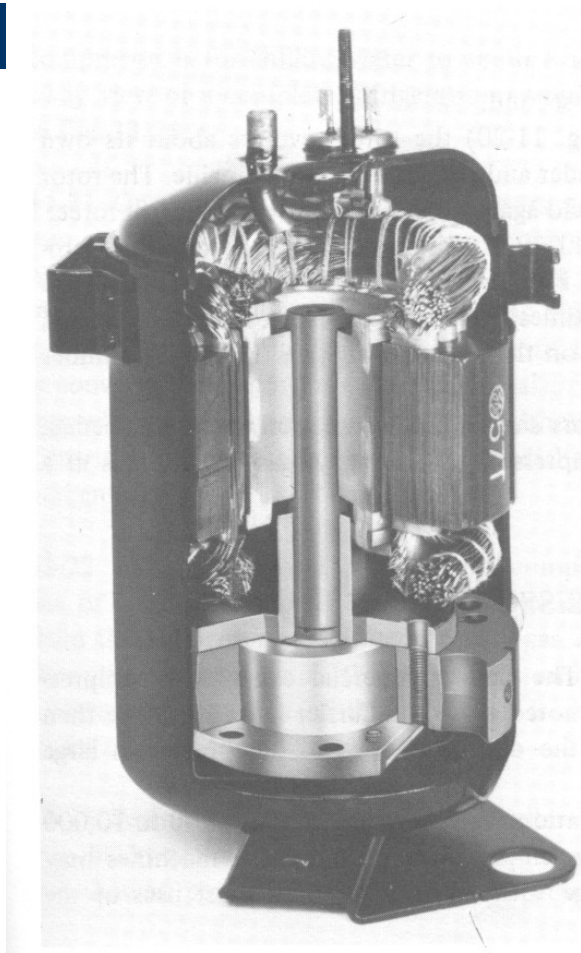
Figure 11-15 Exploded view of main elements of a screw compressor. *(Sullair Refrigeration, Inc.)*

- G e approx. 2.5.

Stoecker and Jones, Refrigeration and Air Conditioning, 2nd ed, Mc-Graw Hill.

Vane Compressors





- No suction valve needed. Minimum gas pulsation

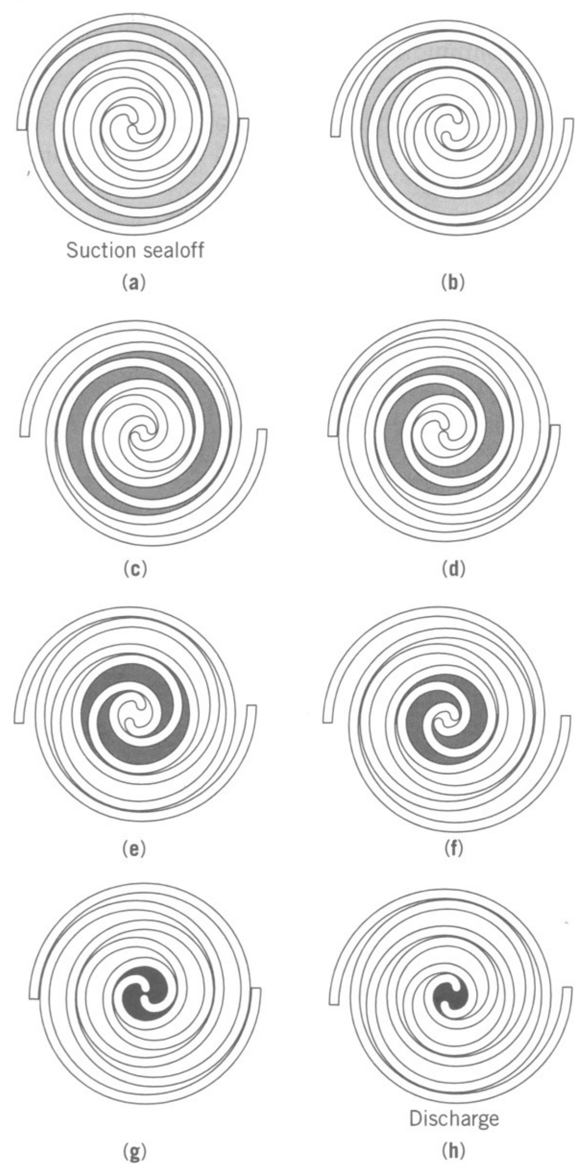
Stoecker and Jones, Refrigeration and Air Conditioning, 2nd ed, Mc-Graw Hill.

Dynamic Compressors -- Centrifugal

- Commonly used for large systems, including chillers
- Gas enters a spinning impeller and is thrown to the outside of the impeller through centrifugal force
- Impeller provides the gas with a high velocity (kinetic energy) which is converted to pressure (internal energy); remember Bernoulli's Law!
- 70-80% isentropic efficiencies
- Axial compressors are a somewhat less common form of dynamic compressors

Scroll Compressors

- Need close machining tolerances
- Low noise, high efficiency
- Incompatible with solid contaminants and poor performance at low suction pressures



From McQuiston, Parker, and Spitler, Heating, Ventilating, and Air Conditioning Analysis and Design

Expansion Valves

Figures are from Stoecker and Jones, Refrigeration and Air Conditioning, 2nd ed., McGraw Hill

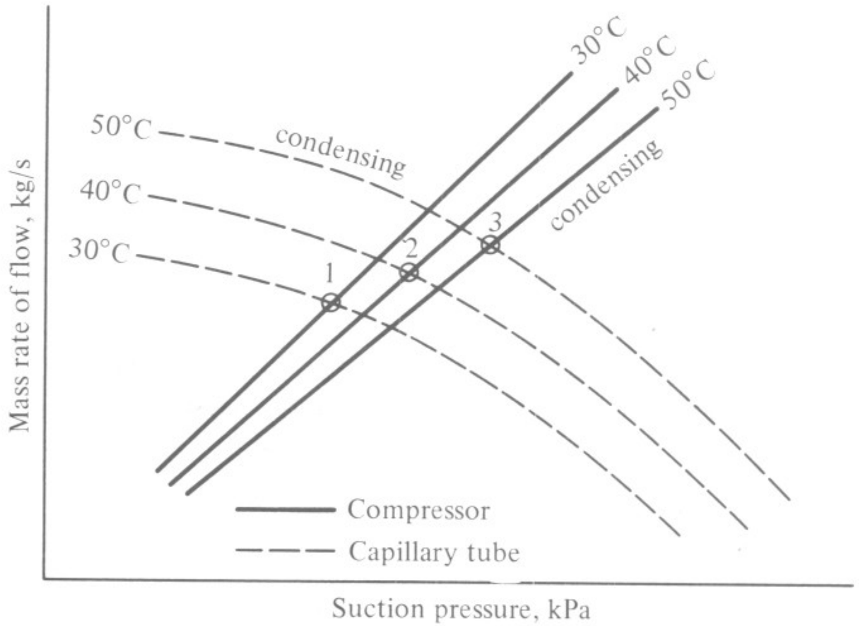
Expansion Devices

- Two purposes
  - Reduce pressure of refrigerant at approx. constant enthalpy, resulting in a large temperature drop
  - Regulate refrigerant flow to the evaporator
- Main types
  - Capillary tubes – used up for refrigerating capacities of approx. 10 kW or less; common in domestic refrigerators
  - Constant-pressure expansion valve – for systems with refrigerating capacity of 30 kW or less
  - Float valves – used in large industrial applications
  - Thermostatic expansion valve - the most popular type of valve, capable of providing a wide range of evaporator temperatures

Capillary Tubes

- 1 to 6 m long, 0.5 to 2 mm inside diameter
- Pressure drops through the tube due to friction and fluid acceleration
- Cap tubes and cheap and reliable, but they can't adjust to changes in parameters such as added load, suction pressure, etc. You'd need to install a new tube to get different system performance. They also can be clogged.
- Mass flow rate is determined by a balance point between cap tube and compressor performance.
- If there is too much or too little heat transfer in the evaporator for the given balance point, the evaporator will be starved or overfed.

Capillary Tubes, cont.



- Starved evaporator– not enough refrigerant to provide enough cooling capacity
- Overfed evaporator – too much refrigerant for the amount of cooling needed, resulting in slugging of the compressor (liquid drops enter the compressor)

Capillary Tubes, cont.

- As a result, refrigerant charge must be within close limits. Therefore, cap tubes are usually used only with hermetically sealed compressors since they don't leak.
- Usually only liquid enters the tube. As the pressure and temperature drop, more and more of the liquid flashes to vapor.
- Vapor has a larger specific volume than liquid, so the fluid must speed up.
- If the pressure drops low enough, choked flow will result. Further decreases in pressure will have no effect on the flow rate through the nozzle. In this case, sonic velocity occurs at the end of the tube!

Capillary Tubes, cont.

Table 13-1 Capillary-tube calculations in Example 13-1

Position	Temperature, °C	Pressure, kPa	quality x	Specific volume, m^3/kg	Enthalpy, kJ/kg	Velocity, m/s	Increment length, m	Cumulative length, m
1	40	1536.4	0.000	0.000885	249.85	4.242		
2	39	1498.8	0.008	0.000995	249.84	4.769	0.2306	0.231
3	38	1461.9	0.016	0.001110	249.84	5.320	0.2013	0.432
4	37	1425.8	0.023	0.001230	249.84	5.895	0.1770	0.609
5	36	1390.3	0.031	0.001355	249.83	6.496	0.1565	0.765
6–31	...	...	...	...	...	...	...	...
32	9	657.65	0.194	0.007660	249.18	36.71	0.0097	2.089
33	8	637.90	0.199	0.008048	249.11	38.57	0.0085	2.098
34	7	618.61	0.204	0.008452	249.03	40.51	0.0075	2.105
35	6	599.78	0.209	0.008873	248.95	42.52	0.0066	2.112
36	5	581.38	0.213	0.009309	248.86	44.61	0.0049	2.118

Table 13-2 Continuation of capillary-tube calculation

Position	Temperature, °C	Pressure, kPa	x	Specific volume, m^3/kg	Enthalpy, kJ/kg	Velocity, m/s	Increment length, m	Cumulative length, m
42	−1	479.97	0.239	0.01231	248.11	59.00	0.0017	2.137
43	−2	464.50	0.243	0.01288	247.95	61.73	0.0012	2.138
44	−3	449.41	0.247	0.01347	247.77	64.56	0.0007	2.139
45	−4	434.71	0.250	0.01409	247.58	67.50	0.0003	2.139
46	−5	420.38	0.254	0.01472	247.37	70.55	−0.0001	

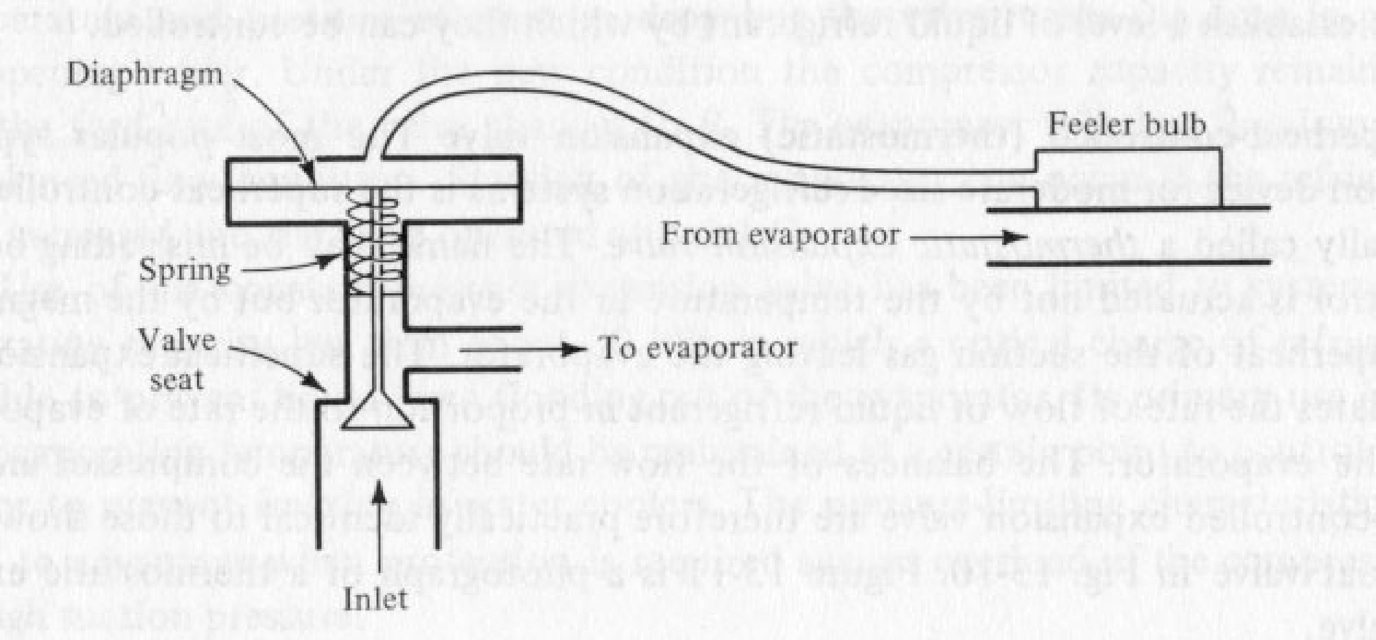
Choked flow

Note 70 m/s=157 mi/hr=252 km/hr

Constant-Pressure Expansion and Float Valves

- Constant-pressure expansion valves maintain constant pressure in the evaporator by opening or closing
  - Used a lot when a very precise evaporator temperature is needed, such as in water coolers (to prevent freezing) or rooms where humidity control is very important (such as banana-curing rooms)
- Float valves maintain the liquid level in the evaporator at a constant level by opening or closing
  - Can react easily to changes in load
  - Used in large installations
  - In smaller installations where continuous-tube evaporators are used, they can’t be used since it’s nearly impossible to establish a liquid level.

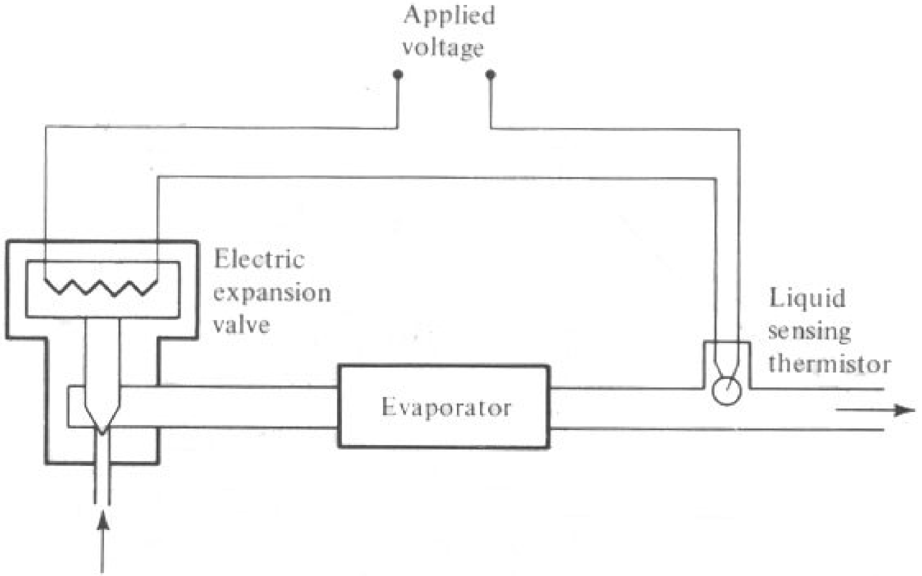
Thermostatic (Superheat-Controlled) Expansion Valve



- Feeler bulb is filled with same refrigerant as in system and is clamped to the outlet of the evaporator. If too little refrigerant is in the evaporator, it will be very superheated at the exit. This will make the refrigerant in the feeler bulb evaporate, increasing the pressure on the diaphragm. This will open the valve further, letting more refrigerant in, decreasing the temperature at the evaporator exit.

Electric Expansion Valve

- Like a thermostatic expansion valve, except a thermister is used to sense the evaporator exit temperature.
- Used for a lot for systems that can be run as either heat pumps or ac units since it’s OK to run fluid through them backwards

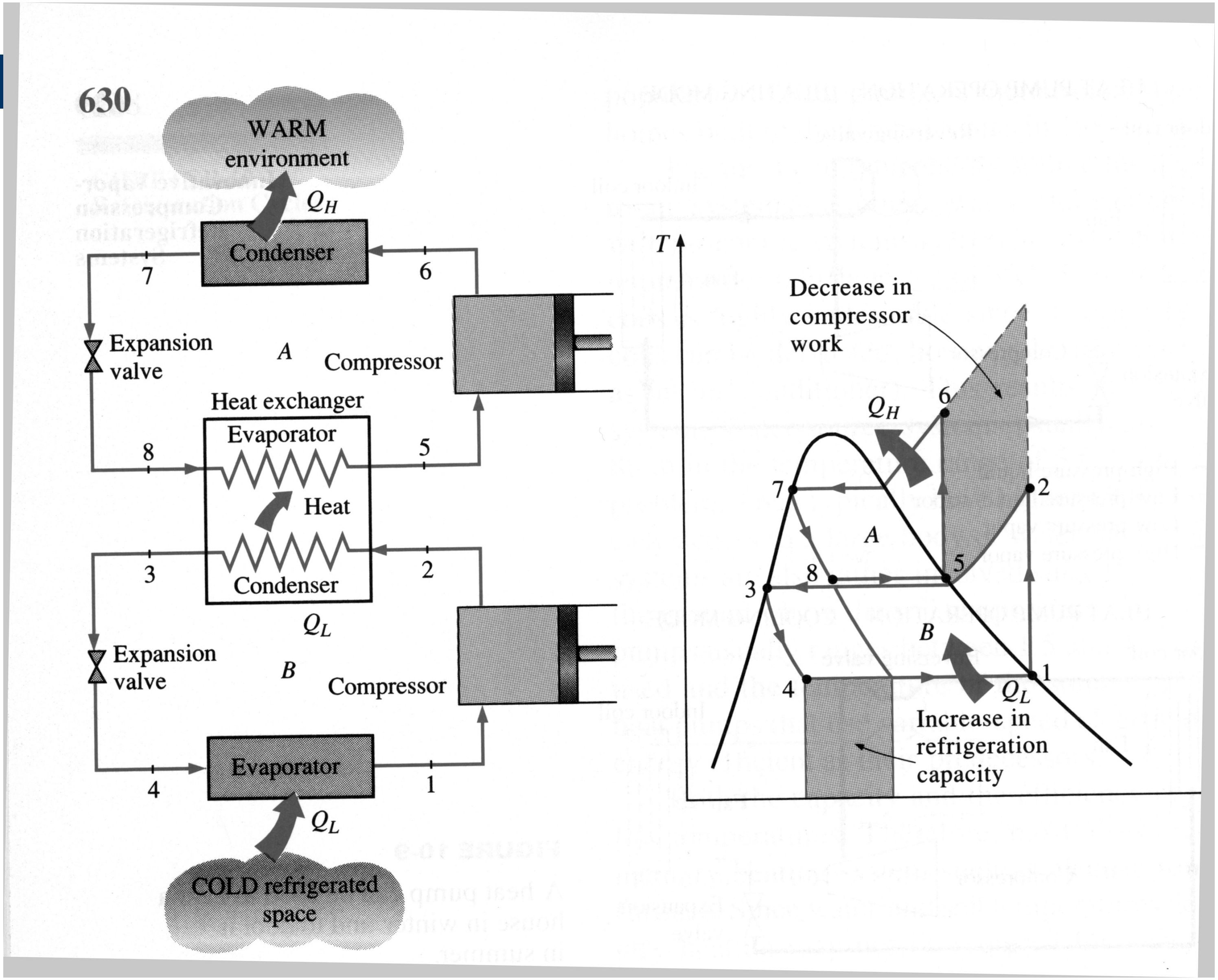


Multi-Pressure Refrigeration Systems

Figures from Refrigeration and Air Conditioning, 2.5 edition, by Stoecker and Jones and Thermodynamics:An Engineering Approach by Çengel and Boles

Cascade Refrigeration Systems

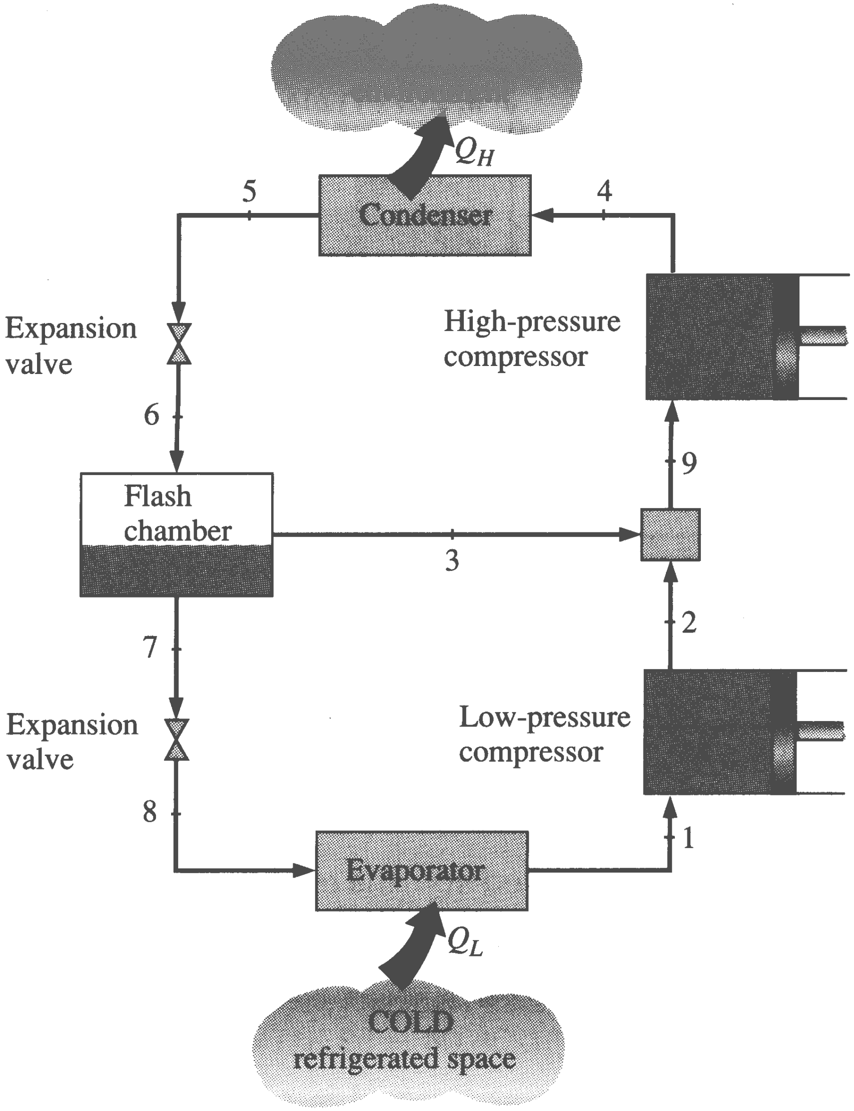
- Used in industrial applications where quite low temperatures are required
- The large temp difference requires a large pressure difference
- Compressors have low efficiencies for large pressure differences; this results in low system efficiency
- Refrigeration cycle is performed in stages
- The refrigerant in the two stages doesn’t mix
- Higher efficiency results but also a higher first cost

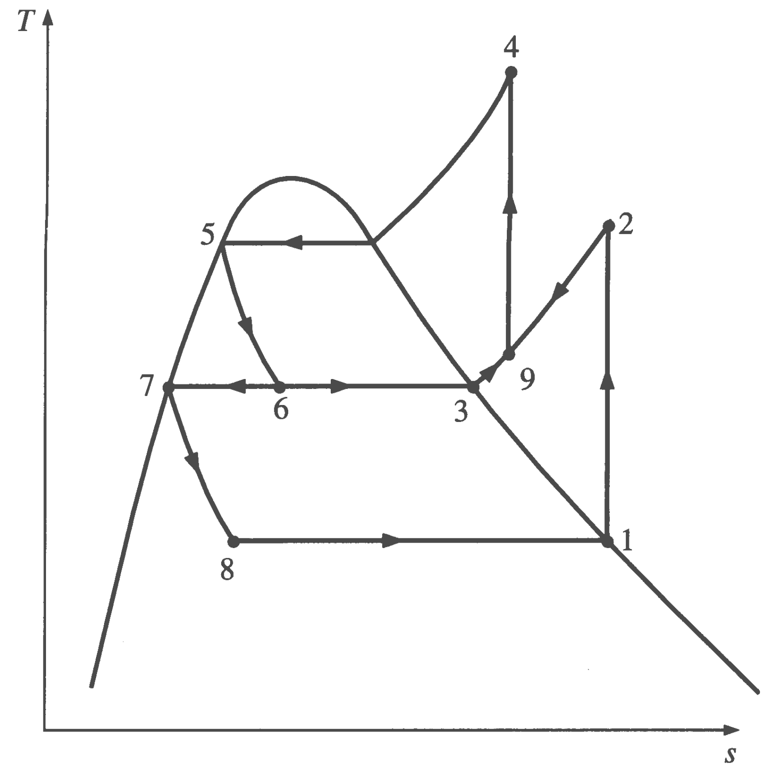


From Cengel and Boles, Thermodynamics: An Engineering Approach

Multistage Compression Refrigeration

- Similar to a cascade system except the same fluid is used for both stages
- Compression is done in two stages with a mixing chamber in between.
- Expansion is also done in two stages. After the first expansion, a liquid/vapor mix is present.
- In the flash chamber, the saturated vapor is removed and sent to the mixing chamber while the liquid goes through the second expansion valve. This ensures that sufficient cooling capacity and mass flow rate through the valve and is achieved.
- Watch your mass flow rates! They're different in different parts of the cycle





From Cengel and Boles, Thermodynamics: An Engineering Approach

Benefits of Flash Gas Removal

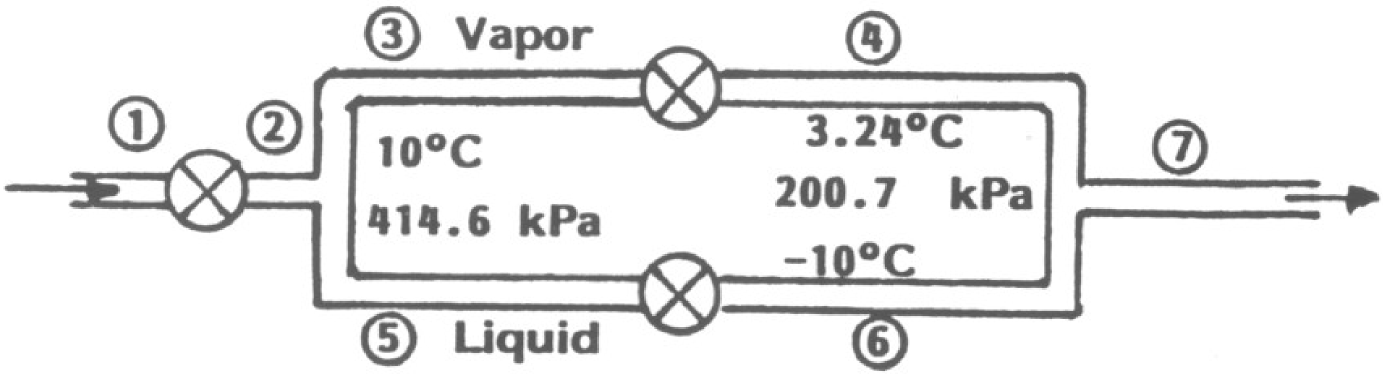


TABLE 17.2

Power required with and without flash gas removal at 2°C when the evaporating temperature is −20°C and the condensing temperature is 30°C for systems developing 100 kW of refrigeration.

Refrigerant	Compressor power, kW (no flash-gas removal)	Compressor power, kW (With flash-gas removal)			Percent saving
		Flash gas	Main	Total	
Ammonia	24.32	1.23	21.70	22.93	5.7
R-22	24.78	2.05	20.44	22.49	9.2
R-134a	25.20	2.50	19.85	22.35	11.3

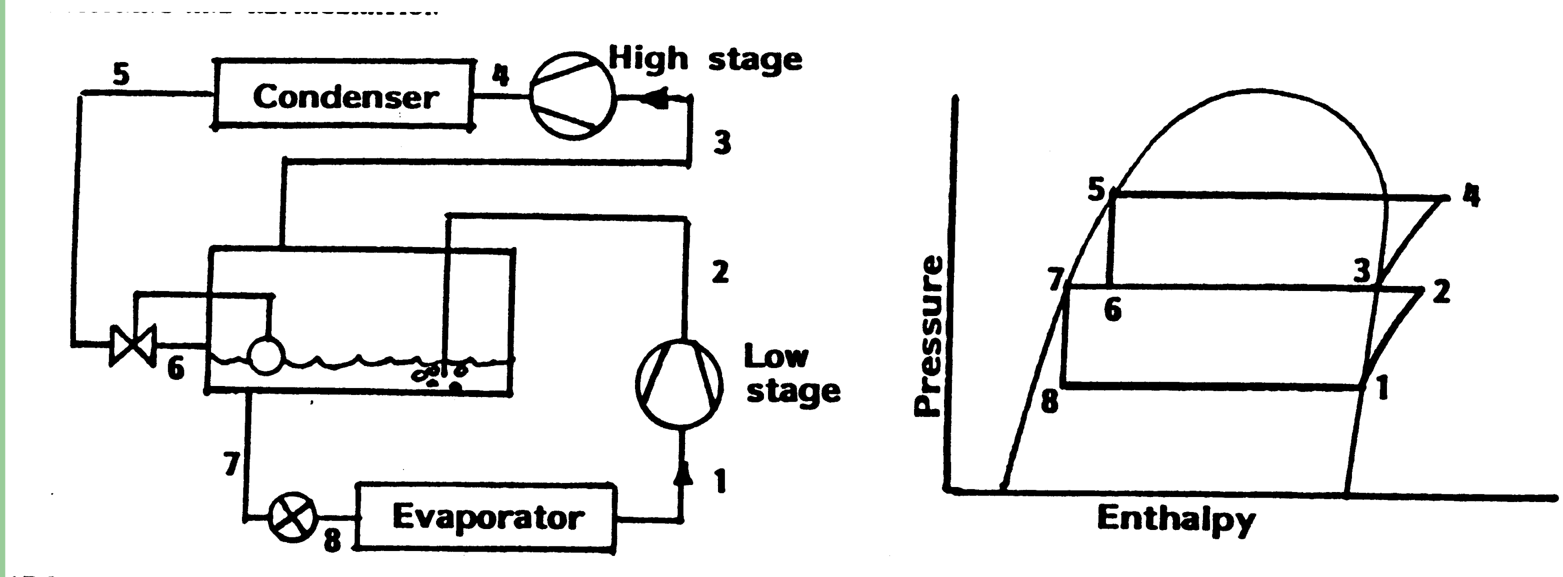
Here ammonia is best

Here R-134a is best

For re-compression of flash gas

From Stoecker and Jones, Refrigeration and Air Conditioning

Flash Gas Removal Plus Intercooling



From Stoecker and Jones, Refrigeration and Air Conditioning

- This is a similar process, but the vapor at 2 is also cooled to the saturation temperature by bubbling it through the liquid in the flash tank. Vapor velocity must be less than 1 m/s for this setup to work well.

Flash Gas Removal Plus Intercooling

- Intercooling alone usually doesn't result in a power reduction for R-134a, but it does for some refrigerants like ammonia (~4%).
- Intercooling may also be done with an external liquid such as water.
- When intercooling and flash gas removal are combined, the savings is similar for most refrigerants.
- A rough estimate of the optimum intermediate pressure can be found from

$$P_{intermediate} = \sqrt{P_{suction} P_{discharge}}$$

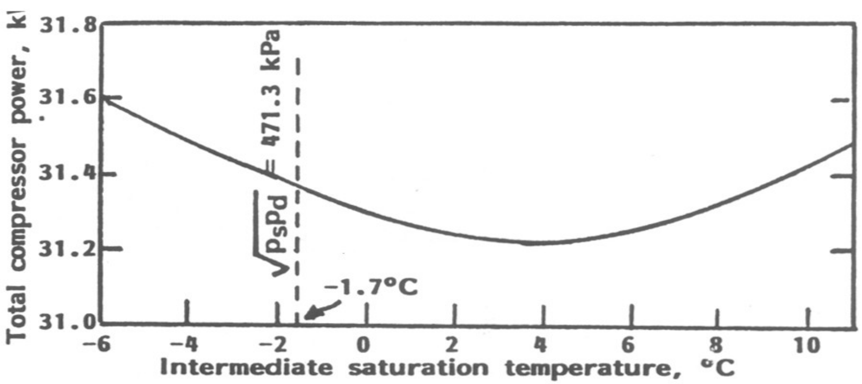


FIGURE 17.10
Total power required in a two-stage R-22 system with a refrigerating capacity of 100 kW as a function of the saturated intermediate temperature. The evaporating temperature is −30°C and the condensing temperature is 35°C.

From Stoecker and Jones, Refrigeration and Air Conditioning

One Compressor & 2 Levels of Evap. Temp

- Often two evaporating temps are required – one for a freezer, and one for a refrigerator
- Why not use one evaporator with a really cold refrigerant temperature for both cases?
  - If you're using the evaporator to chill liquid, the liquid could freeze on the surface of the coils
  - In an air-cooling coil, excessive frost may form
  - If the air-cooling coil cools food, food near the coil could freeze
- Use of two compressors instead of one is more efficient but results in a greater first cost

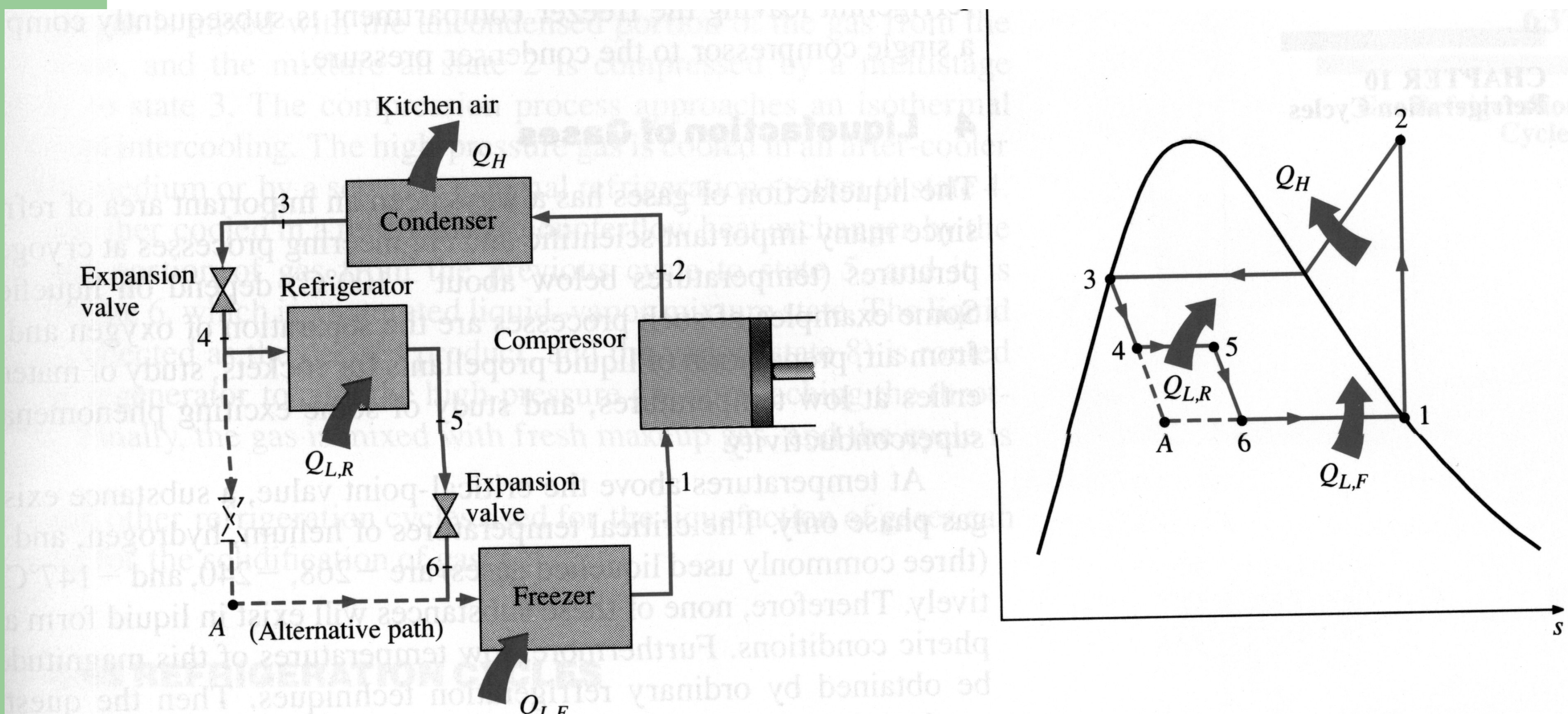
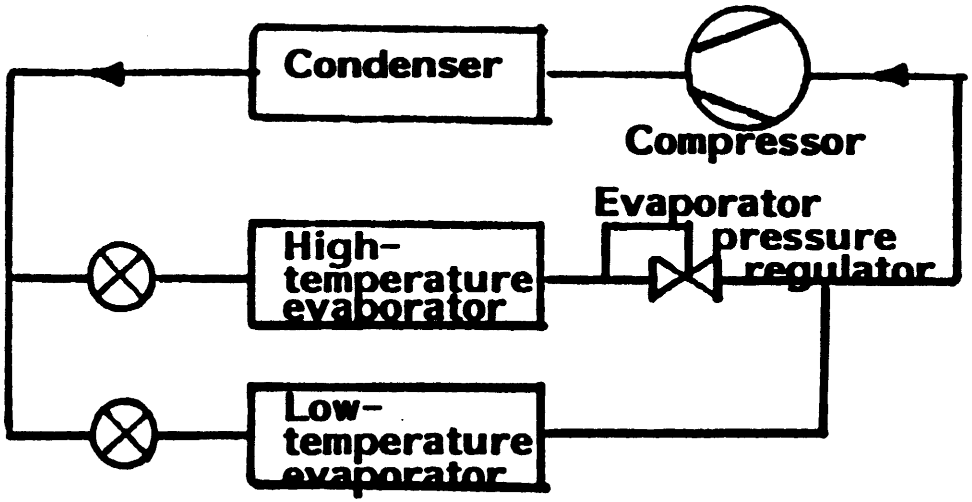


FIGURE 10-14

From Cengel and Boles, Thermodynamics: An Engineering Approach

A more common form of this system



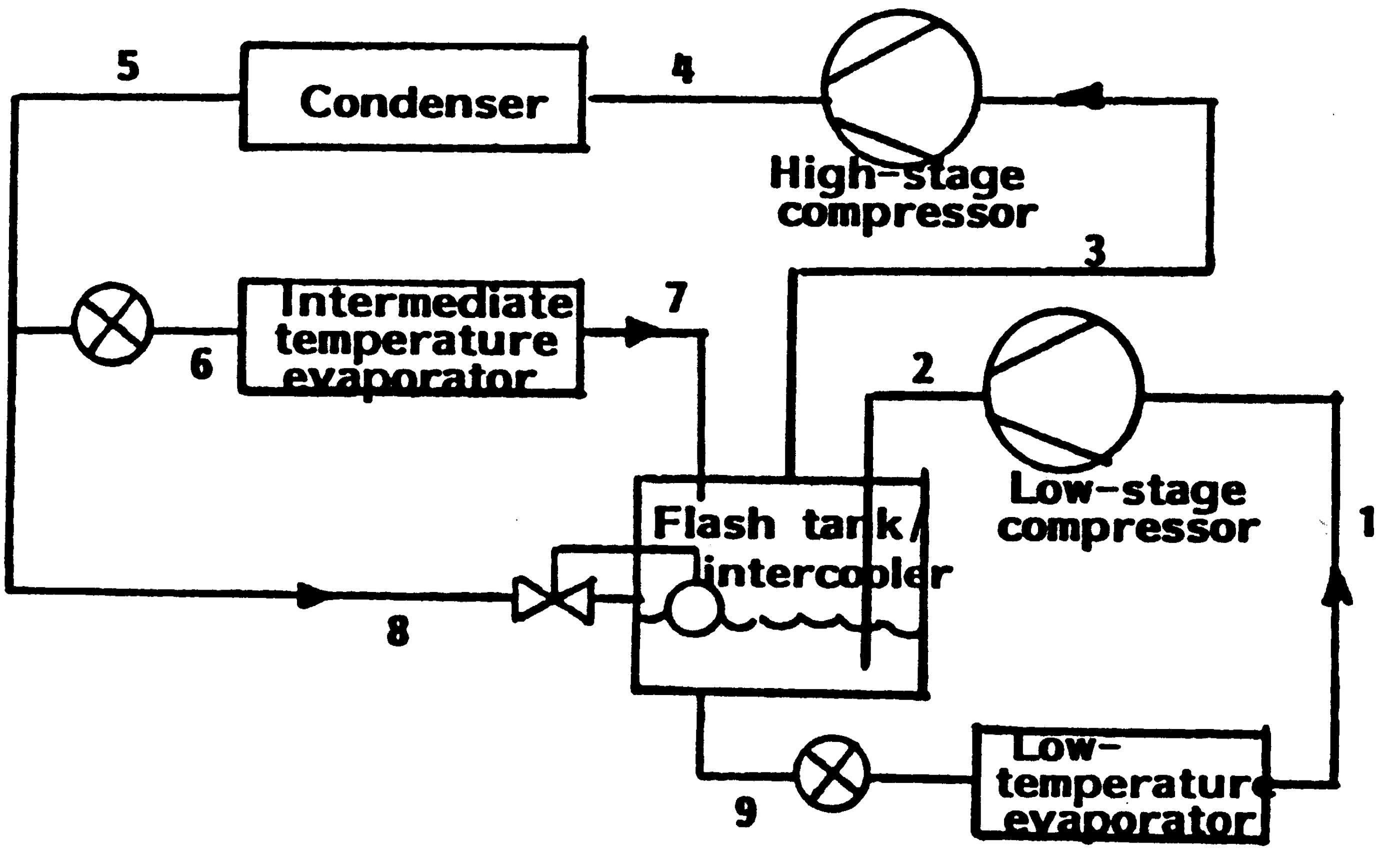
From Stoecker and Jones, Refrigeration and Air Conditioning

- Pressure regulator (sometimes called a back-pressure valve) maintains the higher evaporating temperature in the first evaporator.
- This results in a loss of efficiency but is easier to control than the previous configuration. The pressure regulator may be simply modeled as an expansion valve.

2 Compressors & 2 Evap. Temps

- More efficient but greater first cost than using one compressor
- Used often in a plant storing both frozen & unfrozen foods where required refrigeration capacity is high (well over 100 kW)
- Approximation of optimum intermediate pressure:

$$P_{intermediate} = \sqrt{P_{suction} P_{discharge}}$$



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