

Refrigeration Systems



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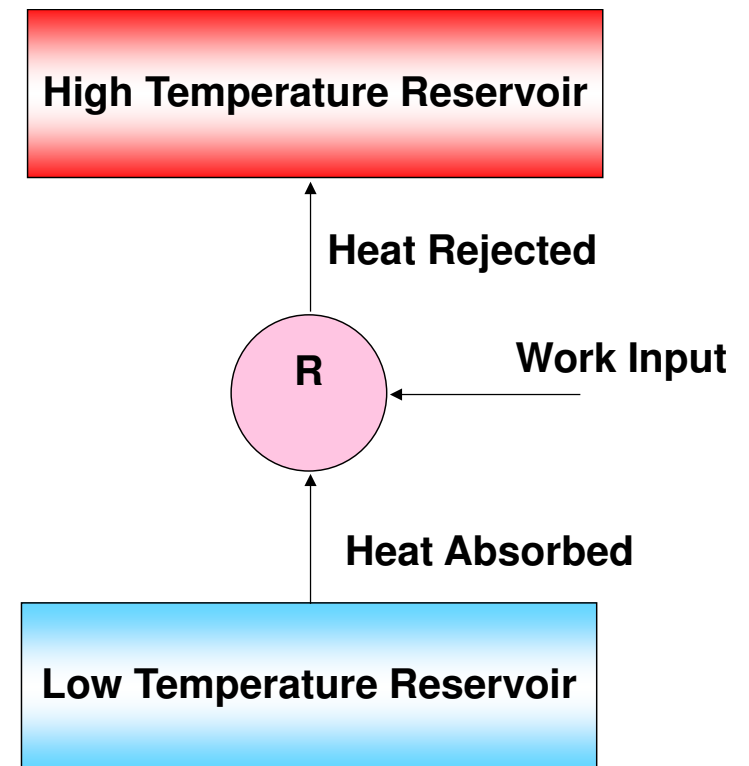
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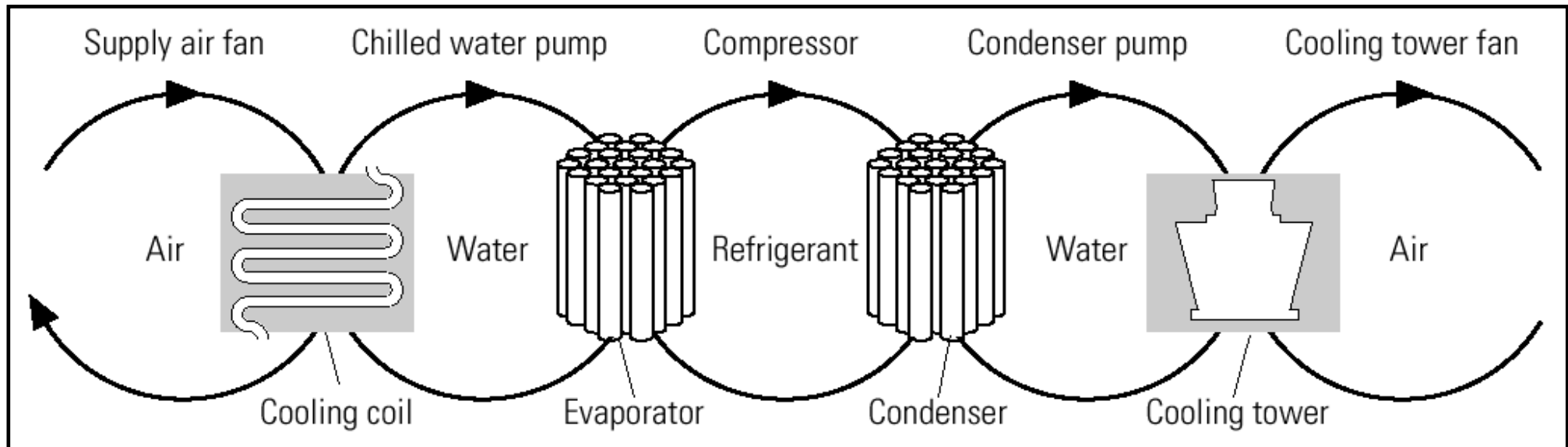


- Introduction
- Refrigerants
- Refrigeration Cycles
- Refrigeration Systems



Thermal energy moves from left to right through five loops of heat transfer (i.e. heat pump)

- 1) **Indoor air loop**
- 2) **Chilled water loop**
- 3) **Refrigerant loop**
- 4) **Condenser water loop**
- 5) **Cooling water loop**



* The knowledge of refrigeration systems would help HVAC engineers in selection of the equipment and fitting it properly into overall system, defining practices consistent with safety and safety standards of the industry, and restrictive regulations on refrigerant production, recovery, and release for environmental concerns.



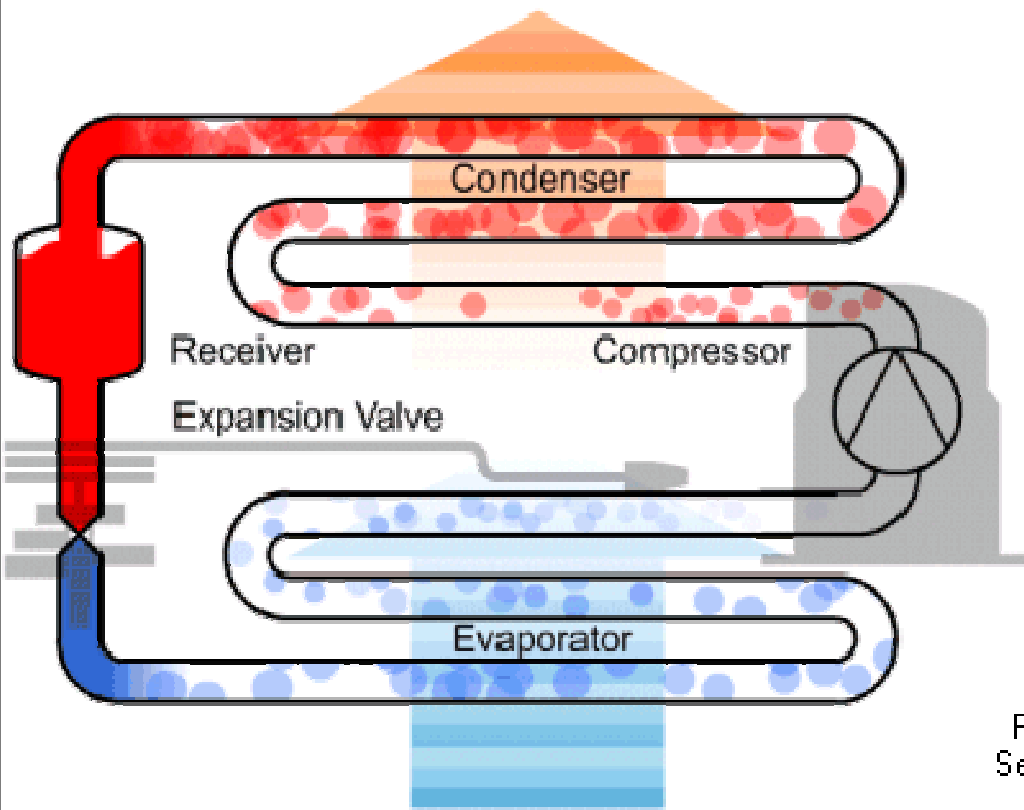
Introduction

- Refrigeration
 - The cooling effect of the process of extracting heat from a lower temperature heat source, a substance or cooling medium, and transferring to a higher temperature heat sink, to maintain the temperature of the heat source below that of surroundings
- Refrigeration systems
 - Combination of components, equipment & piping connected to produce the refrigeration effect



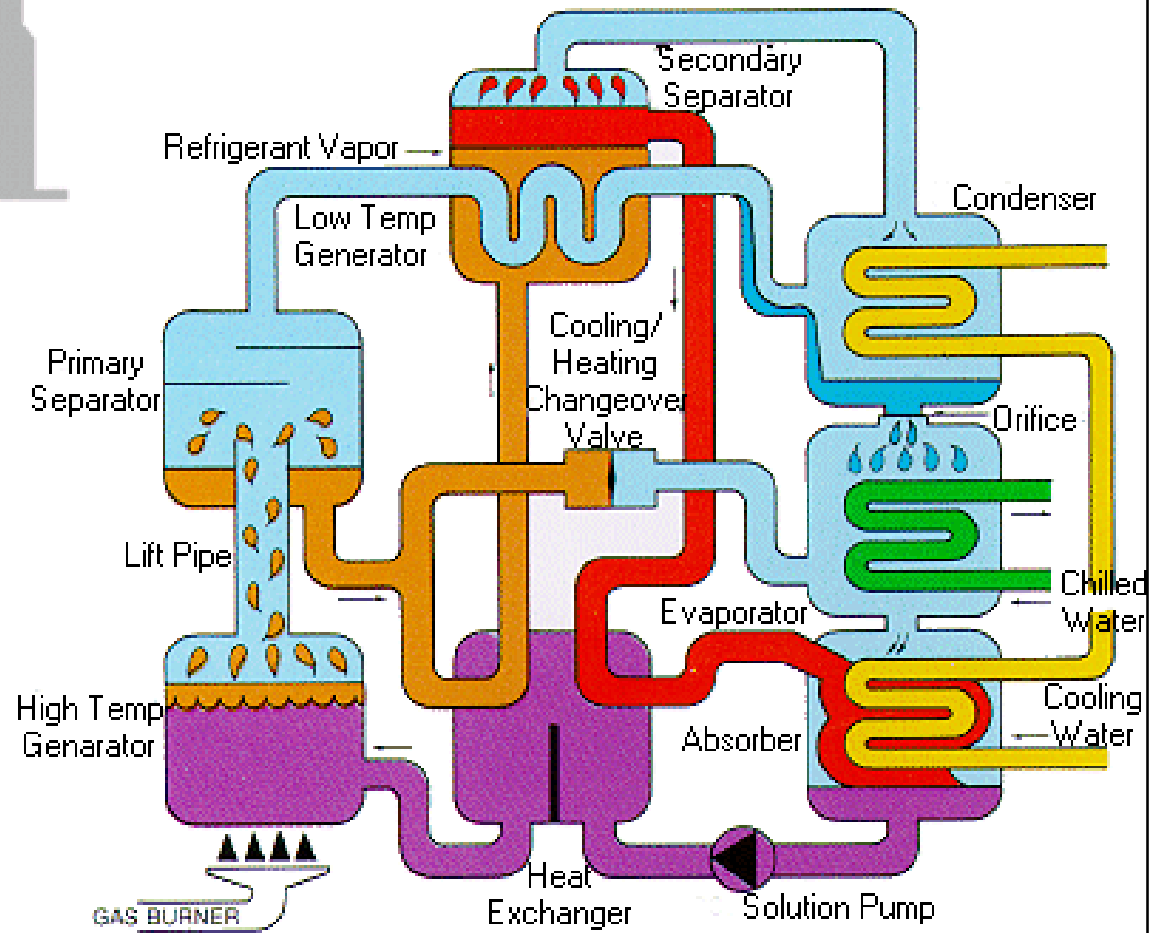
Introduction

- Refrigeration systems
 - Vapour compression
 - Mechanical refrigeration using compressors, condensers and evaporators
 - Absorption
 - Produce refrigeration effect by thermal energy input
 - Liquid refrigerant produce refrigeration during evaporation; the vapour is absorbed by an aqueous absorbent
 - Gas expansion (air or gas cycle)
 - Air or gas is compressed to a high pressure; it is then cooled by surface water or air and expanded to low pressure to produce refrigeration effect
 - For air conditioning and pressurization of aircrafts



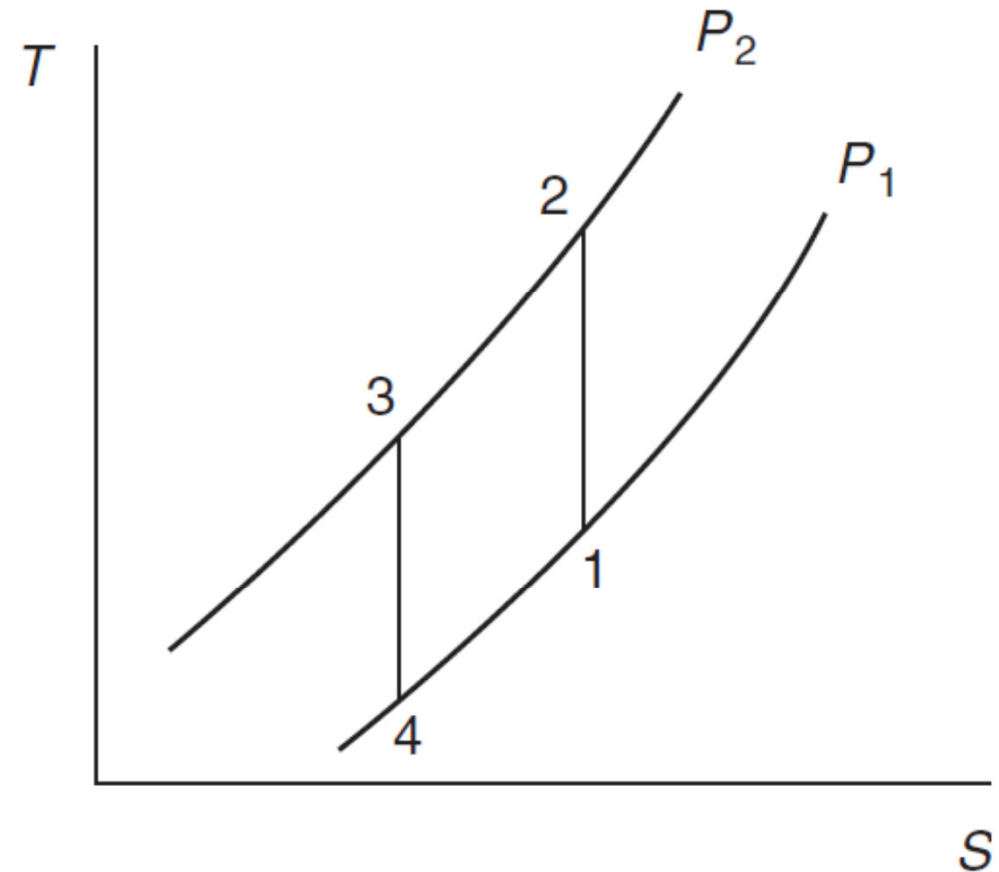
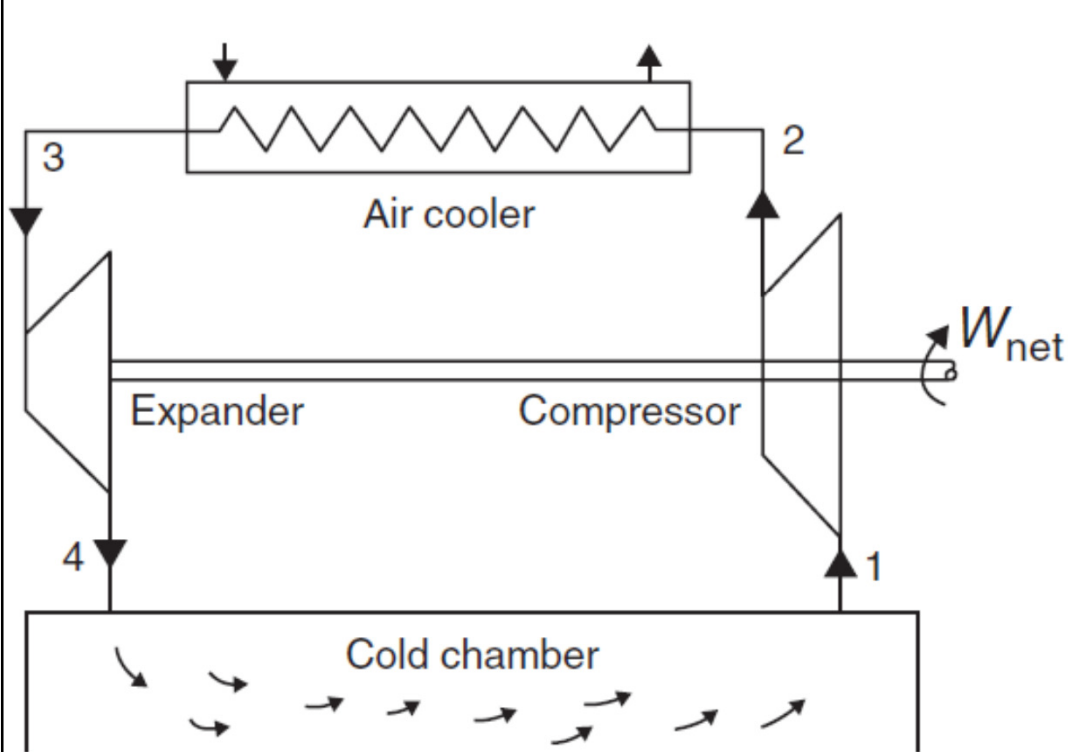
Refrigeration Cycle

Vapour compression system



Absorption system

The air cycle – the work from the expander provides a portion of the work input to the compressor



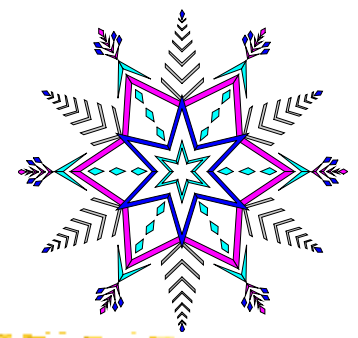
Air cycle refrigeration works on the reverse Brayton or Joule cycle.

Introduction

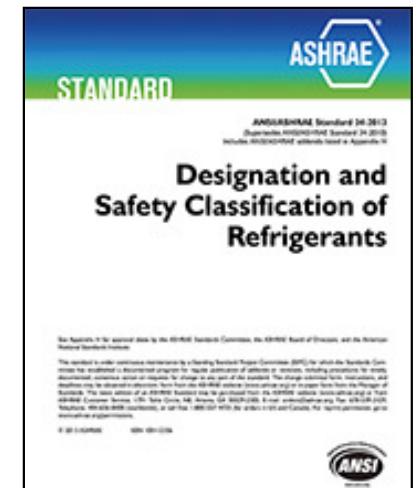


- Terminology
 - Refrigerant:
 - A primary working fluid to produce refrigeration in a refrigeration system
 - Cooling medium:
 - Working fluid cooled by refrigerant during evaporation to transport refrigeration from a central plant to remote equipment
 - Liquid absorbent:
 - Working fluid to absorb vaporised refrigerant (water) after evaporation in an absorption refrigeration system

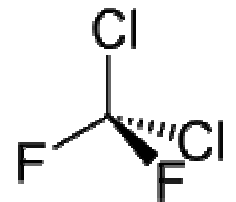
Refrigerants



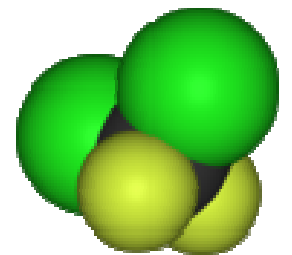
- Numbering system for refrigerants
 - For hydrocarbons & halocarbons (halogenated)
 - ANSI/ASHRAE Standard 34
 - 1st digit: number of unsaturated carbon-carbon bonds
 - 2nd digit: number of carbon atoms minus one
 - 3rd digit: number of hydrogen atoms plus one
 - Last digit: number of fluorine atoms



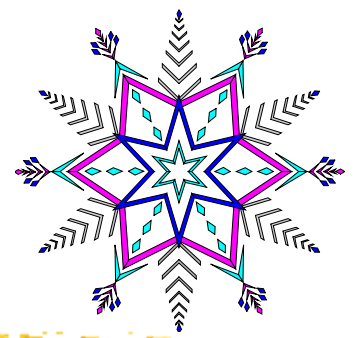
- For example, R-11 = CFCl_3 ; R-12 = CF_2Cl_2 ; R-22 = CHF_2Cl ; R-123 = CHCl_2CF_3



- Chlorofluorocarbons (CFCs)
 - Contains only chlorine, fluorine & carbon atoms
 - Cause ozone depletion & global warming

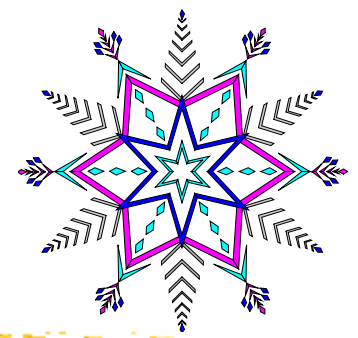


Refrigerants



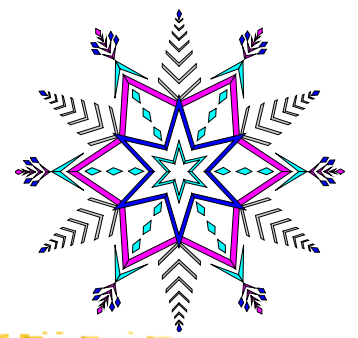
- Impacts of refrigerants
 - Ozone depletion potential (ODP)
 - Ratio of ozone depletion rate compared with R-11
 - Global warming potential (GWP)
 - Global warming effect compared with R-11
- Hydrofluorocarbons (HFCs)
 - Contains only hydrogen, fluorine, and carbon atoms and cause no ozone depletion
 - R-134a, R-32, R-125 and R-245ca

Refrigerants



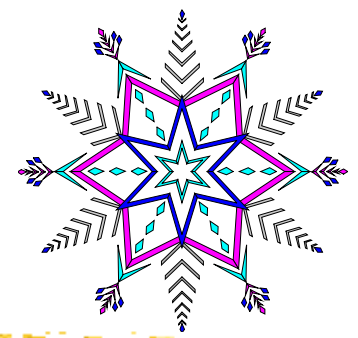
- HFC's azeotropic blends or azeotropic (共沸)
 - Azeotropic = mixture of multiple refrigerants that evaporate & condense as a single substance and do not change in volumetric composition or saturation temperature when evaporate or condense
 - ASHRAE assign numbers 500 to 599 for azeotropic
 - Such as R-507 (blend of R-125/R-143)
- HFC's near azeotropic
 - Mixture of refrigerants whose characteristics are near those of an azeotropic
 - ASHRAE assign numbers 400 to 499 for zeotropic
 - Such as R-404A (R-125/R-134a/R-143a) and R-407B (R-32/R-125/R-134a)

Refrigerants



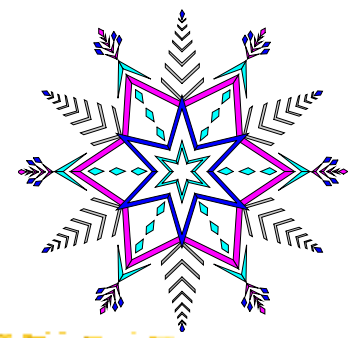
- Zeotropic or non-azeotropic
 - Including near azeotropic
 - Show a change in composition due to the difference between liquid & vapour phases, leaks, and the difference between charge & circulation
 - A shift in composition causes change in evaporating & condensing temperature/pressure
 - Middle between dew point & bubble point is often taken as evap. & cond. temp. for the blends

Refrigerants



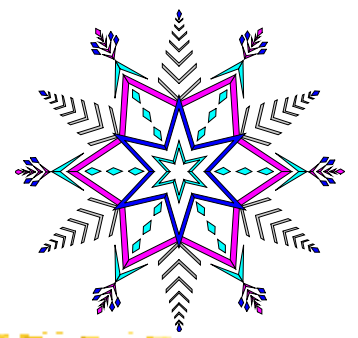
- Hydrochlorofluorocarbons (HCFCs)
 - Contain hydrogen, chlorine, fluorine & carbon atoms and are not fully halogenated
 - Smaller lifetime in atmosphere than CFCs & cause far less ozone depletion (ODP = 0.02 to 0.1)
 - R-22, R-123, R-124
 - HCFC's near azeotropic & HCFC's zeotropic
 - Blends of HCFCs with HFCs
 - Transitional or interim refrigerants, scheduled for restricted production starting in 2004

Refrigerants



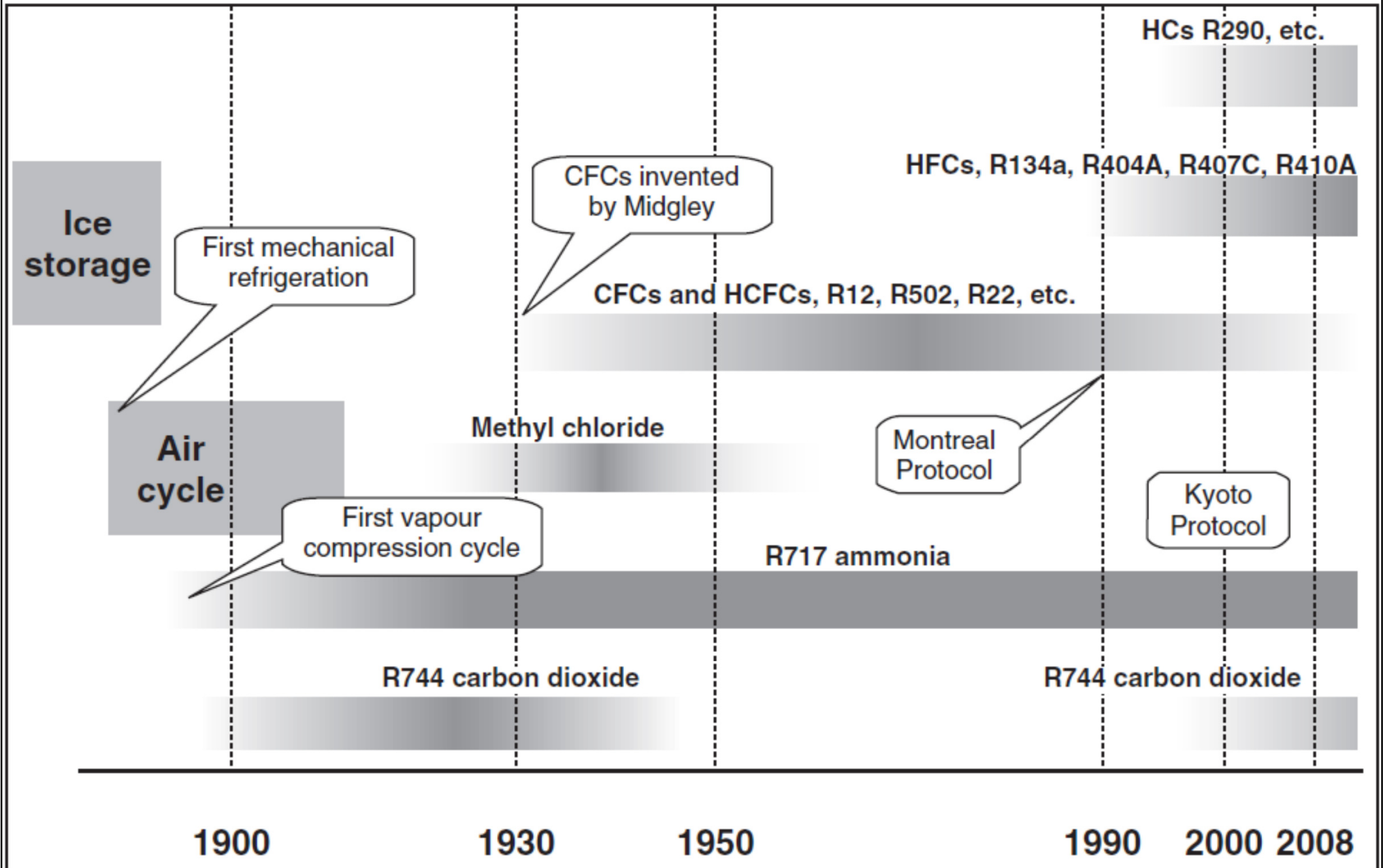
- Inorganic compounds
 - ASHRAE assign numbers R-700 to -799
 - Ammonia (NH_3) R-717, carbon dioxide (CO_2) R-744, air R-729, water (H_2O) R-718, sulphur dioxide (SO_2) R-764
 - Do not deplete ozone layer
- CFCs
 - Long lifetime (centuries)
 - Cause ozone depletion ($\text{ODP} = 0.6 - 1$)
 - Such as R-11, R-12, R-113, R-114, R-115

Refrigerants

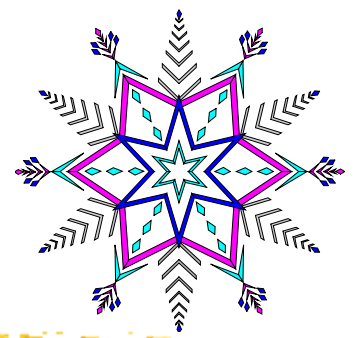


- Halons (or BFCs)
 - Contain bromide, fluorine & carbon atoms
 - R-13B1, R-12B1 (used in very low temp. systems)
 - Very high ozone depletion (ODP for R-13B1 =10)
- Montreal Protocol (1987) & Vienna Convention (1985)
 - Restrict the production & consumption of CFCs & BFCs
 - Phase-out of CFCs, BFCs, HCFCs and their blends

Time line for refrigerants

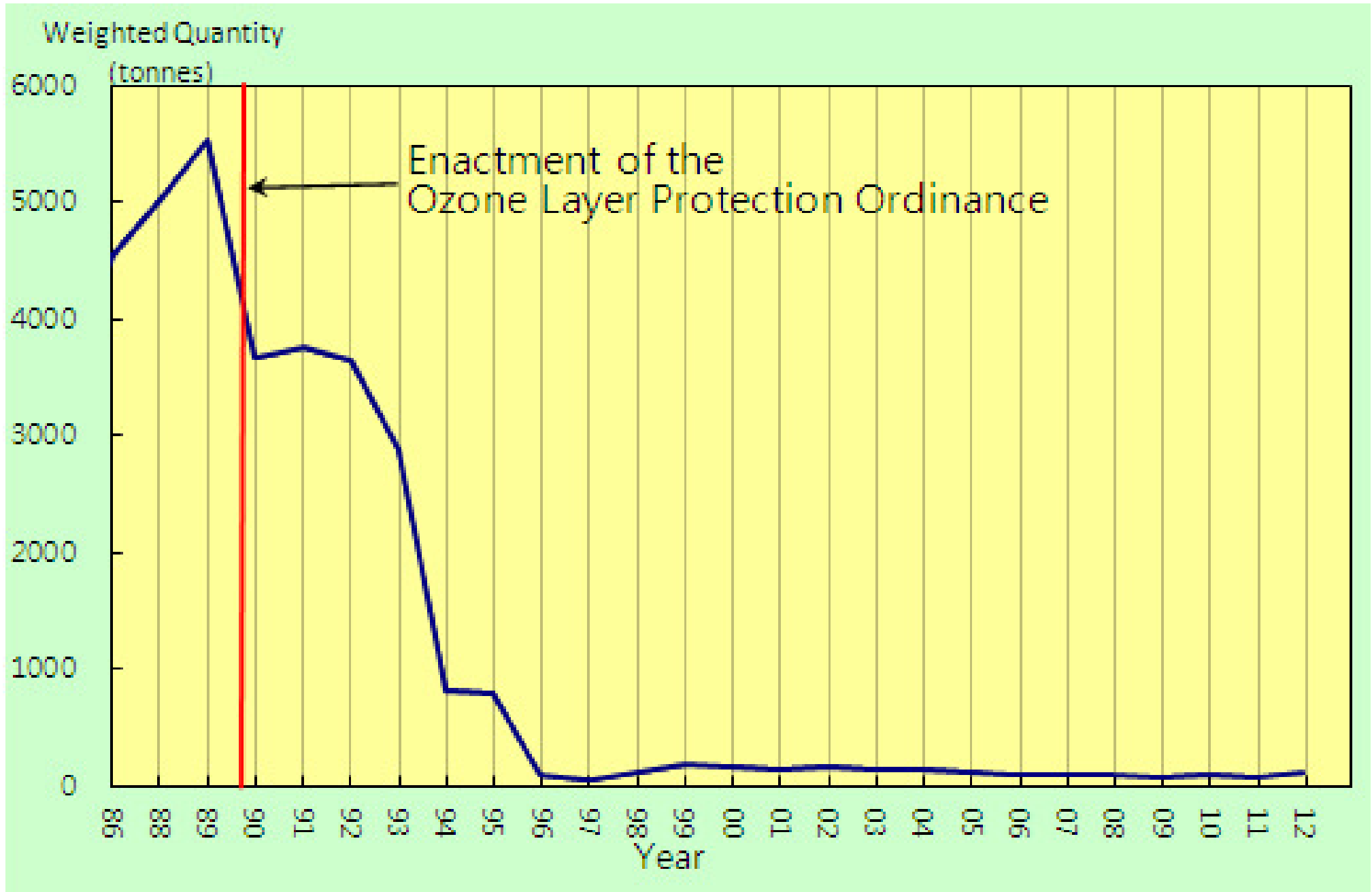


Refrigerants

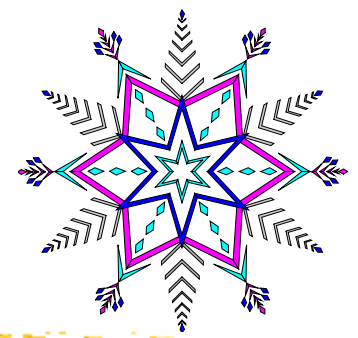


- In early 1990s
 - R-11: widely used for centrifugal chillers
 - R-12: for small & medium systems
 - R-22: for all vapour compression systems
 - R-502 (CFC/HCFC blend) for low-temp. systems
- Hong Kong
 - Ozone Layer Protection Ordinance
 - See website of Environmental Protection Dept.
<http://www.epd.gov.hk/epd/english/olp/>

Ozone Layer Protection Ordinance in Hong Kong

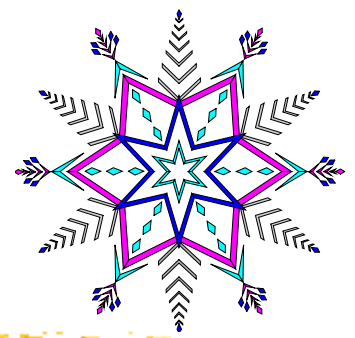


Refrigerants



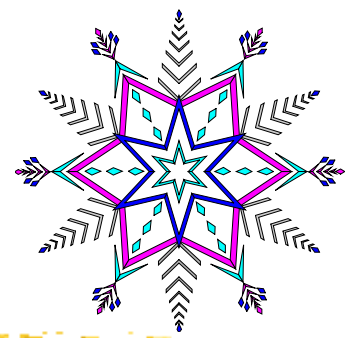
- Alternative refrigerants
 - **R-123** (HCFC, ODP = 0.02), replace R-11
 - R-245a (ODP = 0), replace R-11 (longer term?)
 - **R-134a** (HFC, ODP = 0), replace R-12
 - Not miscible with mineral oil, synthetic lubricant is used
 - **R404A** (R-125/R-134a/143a) and **R-407C**
 - HFCs near azeotropic, ODP = 0; long-term alternatives to R-22
 - **R-507** (R-125/R-134a)
 - HFC's azeotropic, ODP = 0; long-term alternatives to R-502
 - Synthetic lubricant oil is used
 - R-402A (R-22/R-125/R-290) as short-term drop-in replacement

Refrigerants



- Required properties of refrigerants
 - Safety (ANSI/ASHRAE Standard 34-1992)
 - Toxicity: Class A and Class B
 - Flammability:
 - Class 1 – no flame propagation
 - Class 2 – lower flammability
 - Class 3 - higher flammability
 - Such as “A1” Group: R-134a & R-22; “B2”: ammonia
 - Effectiveness of refrigeration cycle (kW/TR)
 - Lubricant oil miscibility
 - Compressor displacement

Refrigerants



- Desired properties:
 - Evaporative pressure $>$ atmospheric
 - Non-condensable gas will not enter the system
 - Lower condensing pressure (lighter construction)
 - High thermal conductivity (better heat transfer)
 - Dielectric constant compatible w/ air
 - An inert refrigerant (avoid corrosion, erosion)
 - Refrigerant leakage can be detected

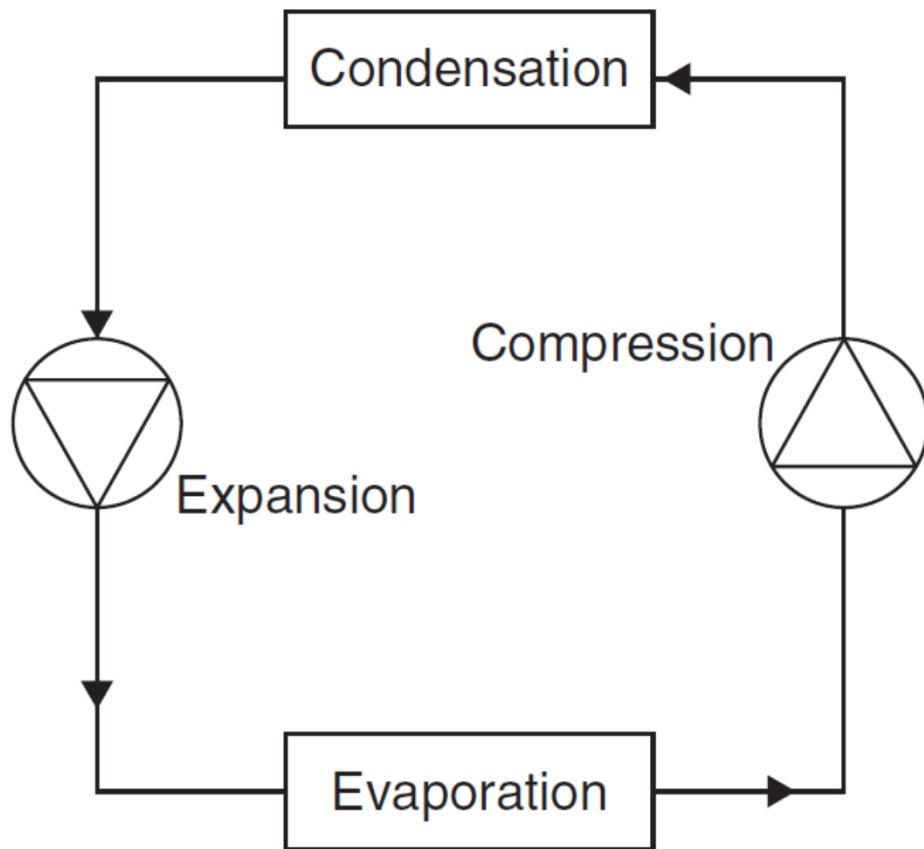


Refrigeration Cycles

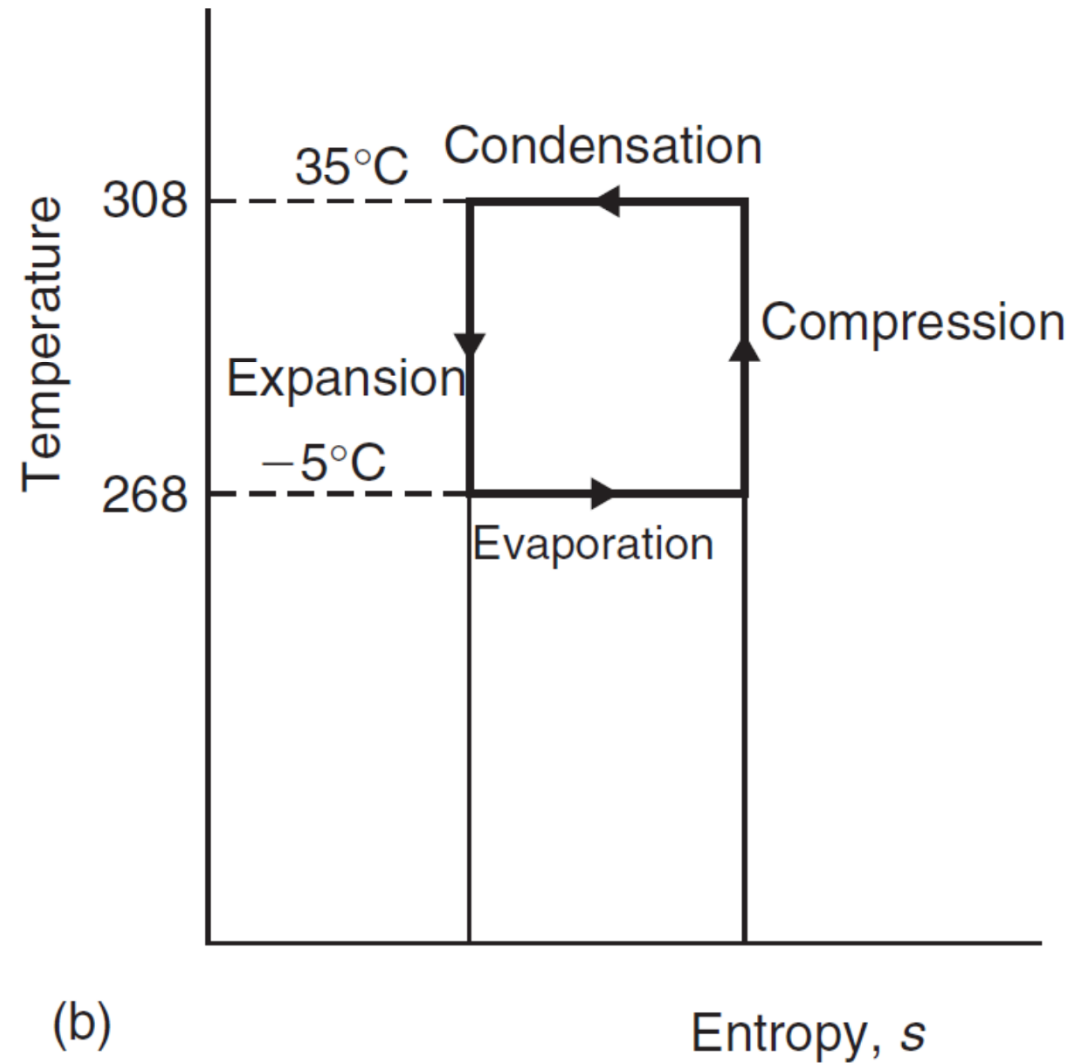
- Refrigeration process
 - Change of thermodynamic properties and the energy & work transfer
 - 1 ton of refrign. (TR) = 12,000 Btu/h (3.516 kW)
- Refrigeraton cycles
 - Closed cycle and open cycle
 - Vapour compression cycles:
 - Single-stage, multi-stage, compound, cascade
 - Pressure-enthalpy ($p-h$) or Mollier diagram
 - Temperature–entropy ($T-s$) diagram

The ideal reversed Carnot cycle:

(a) circuit and (b) temperature–entropy (T - s) diagram



(a)



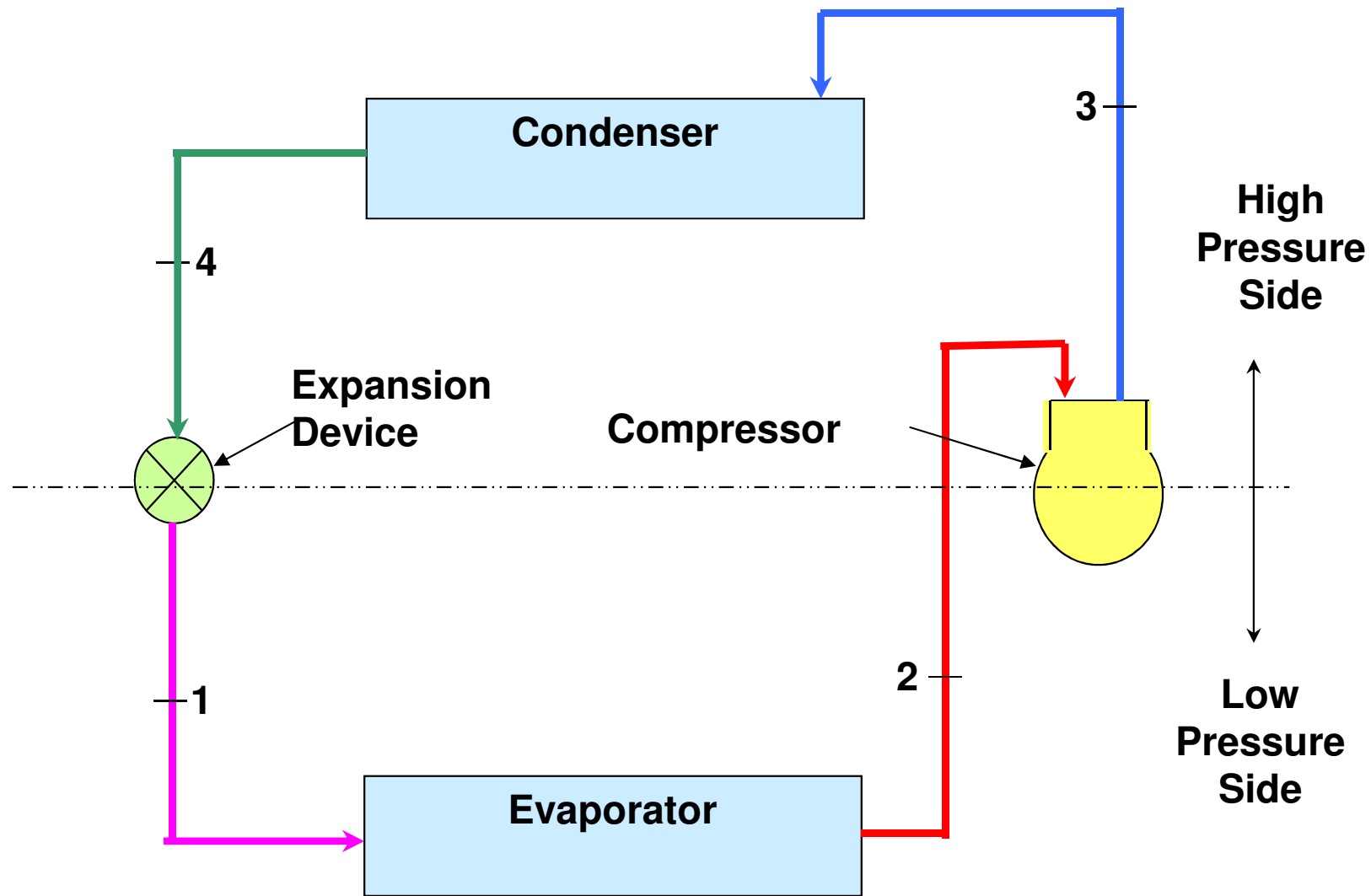
(b)



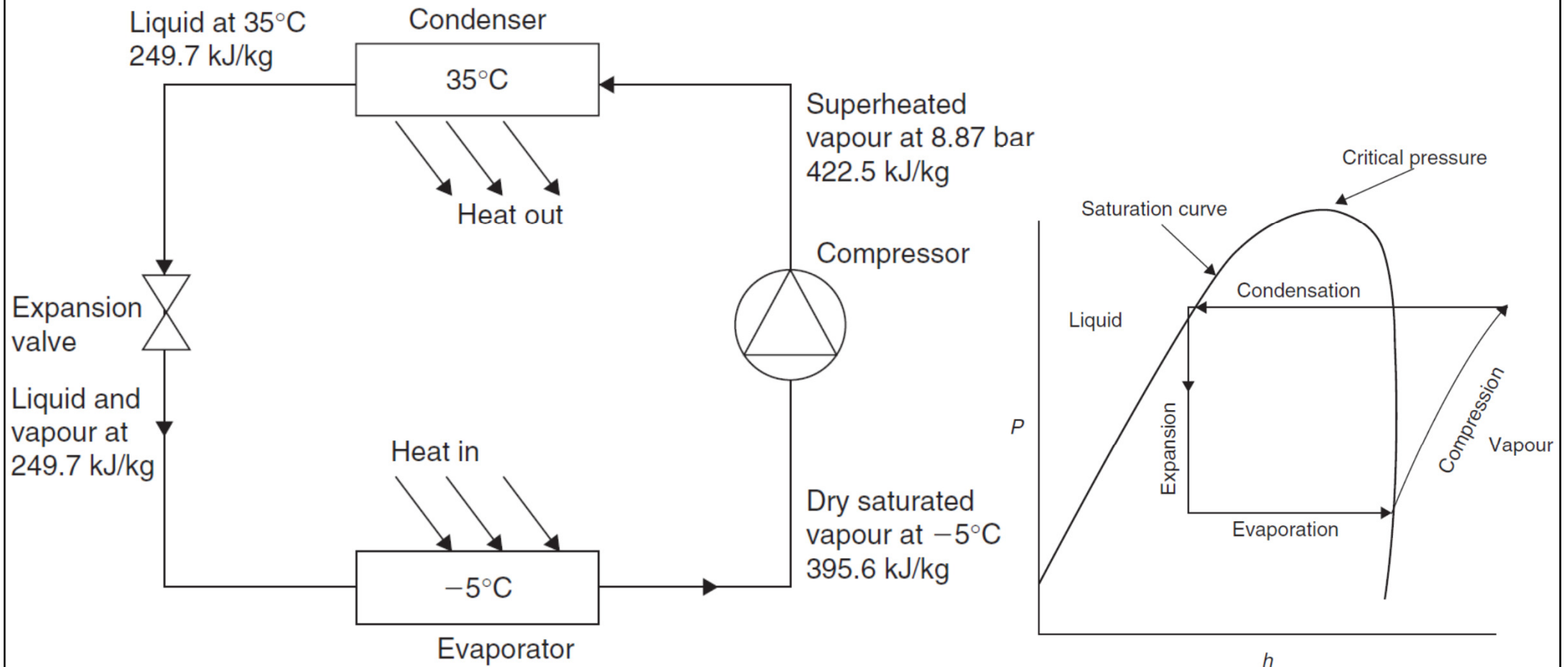
Refrigeration Cycles

- Ideal single-stage cycle
 - Isentropic compression, pressure losses neglected
 - q_{rf} = refrigeration capacity
 - W_{in} = work input to compressor
- Coefficient of performance (COP)
 - $COP = q_{rf} / W_{in}$
 - Refrigerator: produce refrigeration effect
 - Heat pump: produce heating effect
- Subcooling and superheating

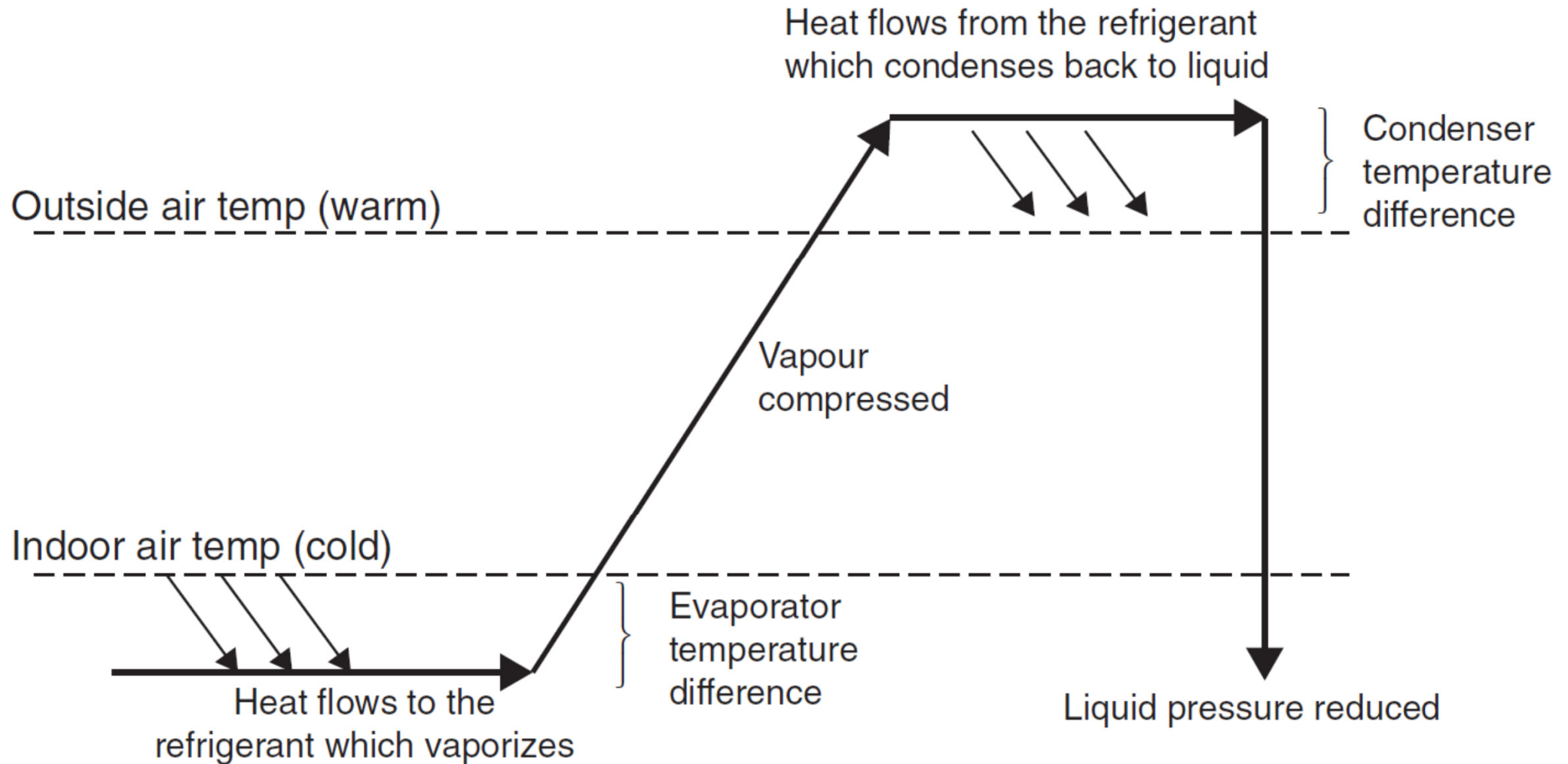
Refrigeration cycle -- vapour compression cycle



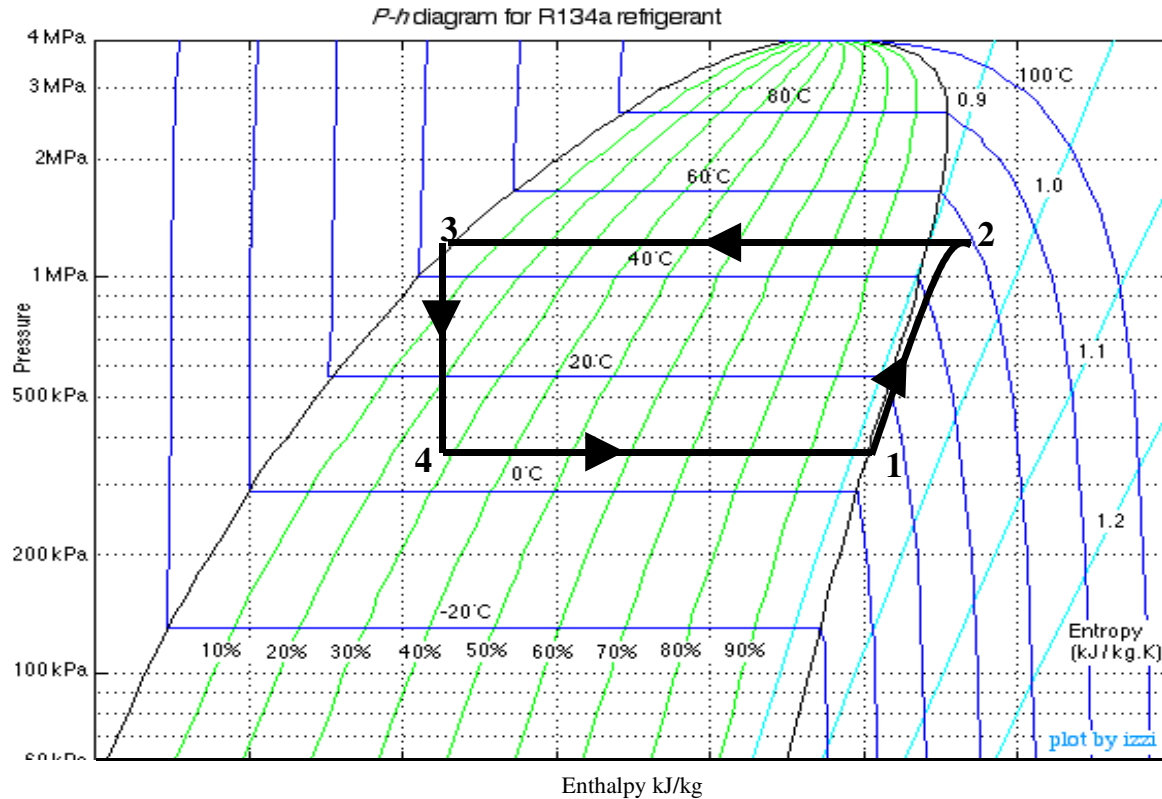
Simple vapour compression cycle with pressure and enthalpy values for R134a



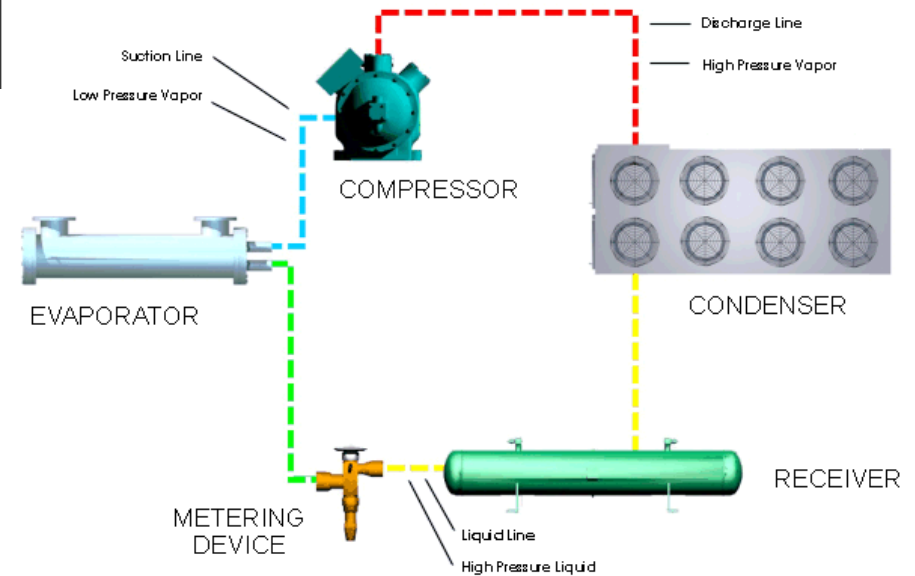
The temperature rise or ' lift ' of the refrigeration cycle is increased by temperature differences in the evaporator and condenser

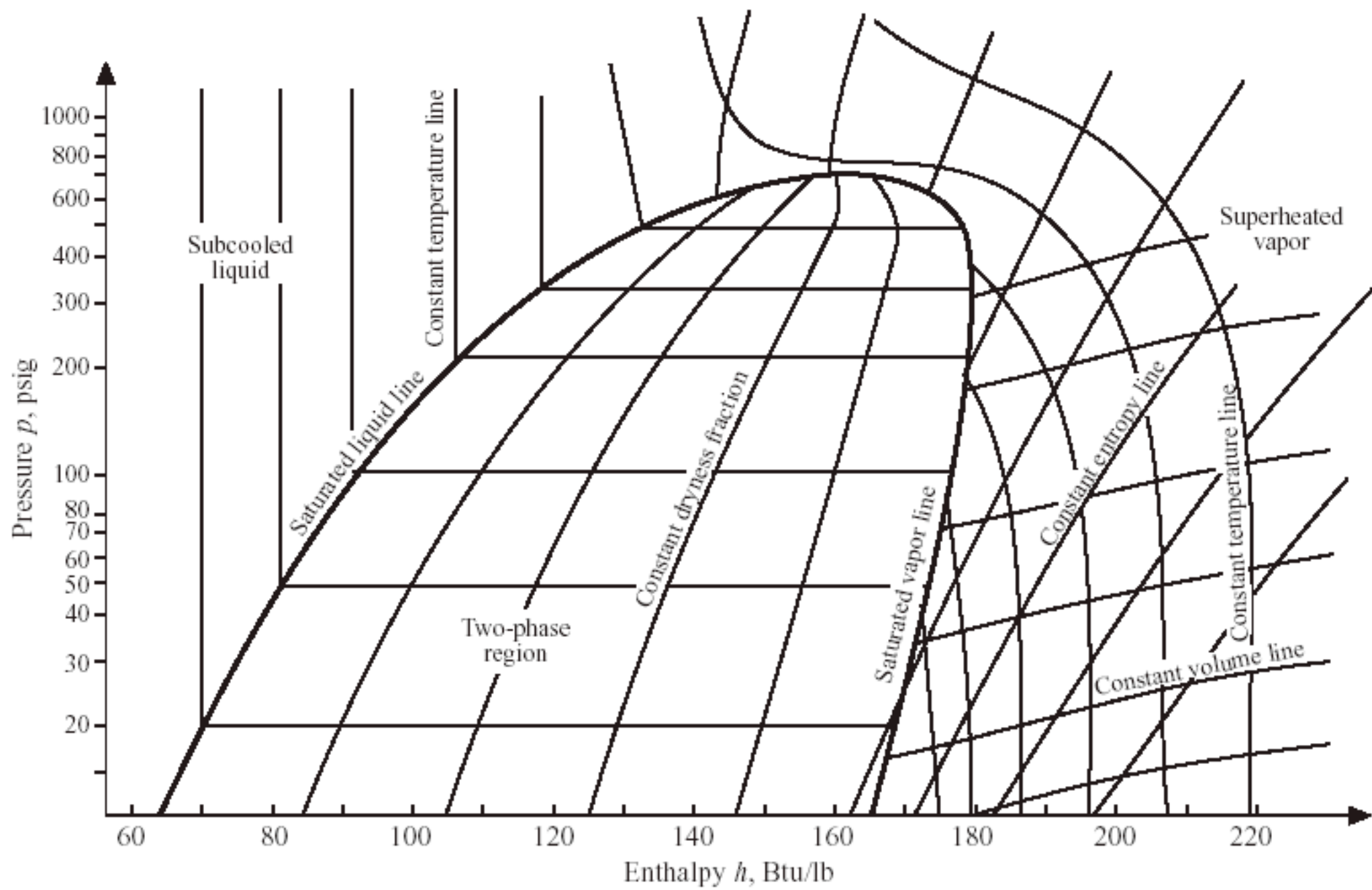


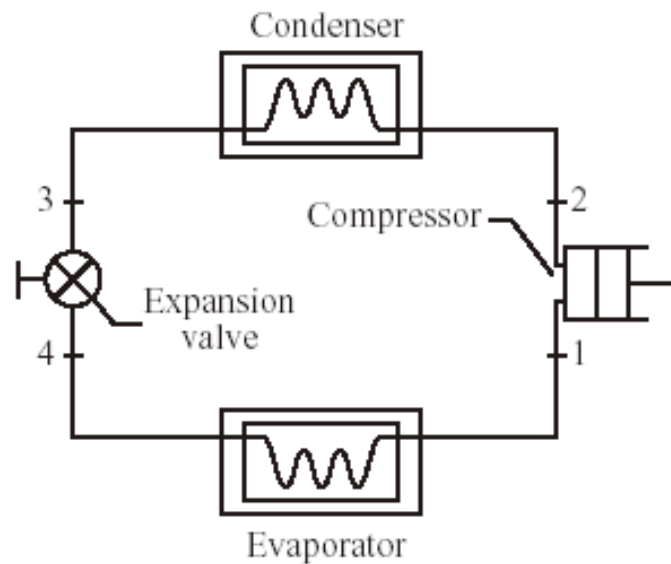
Refrigeration cycle -- vapour compression cycle



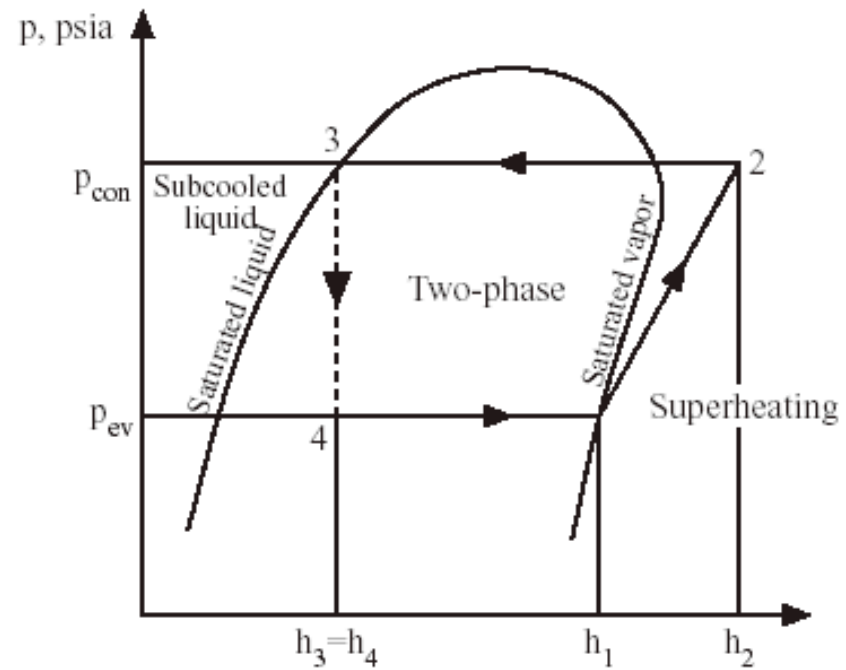
System COP normally includes all the power inputs associated with the system, i.e. fans and pumps in addition to compressor power. A ratio of System COP to Carnot COP (for the process) is termed *system efficiency index*, **SEI**.



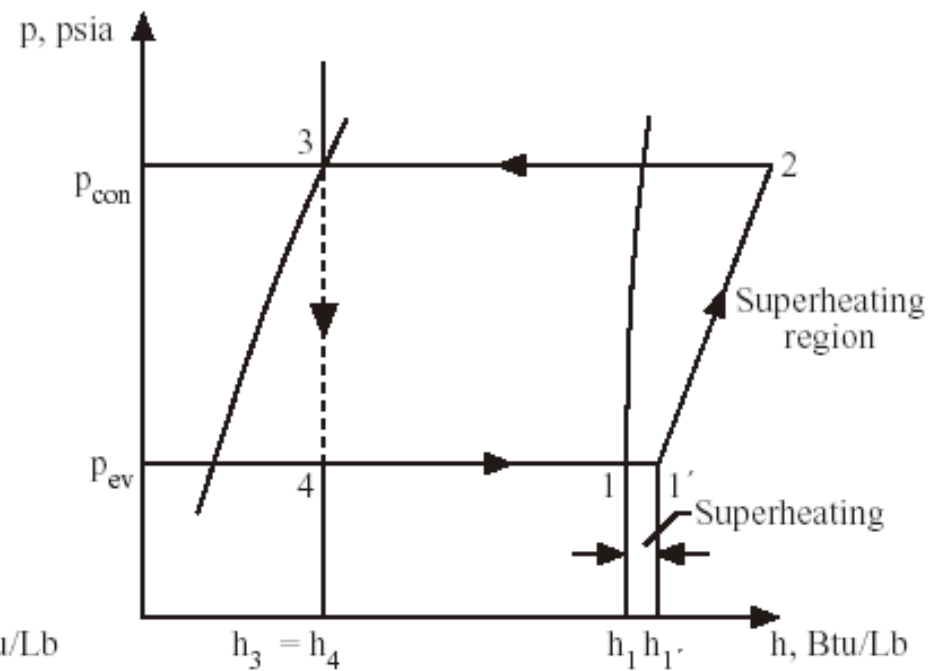
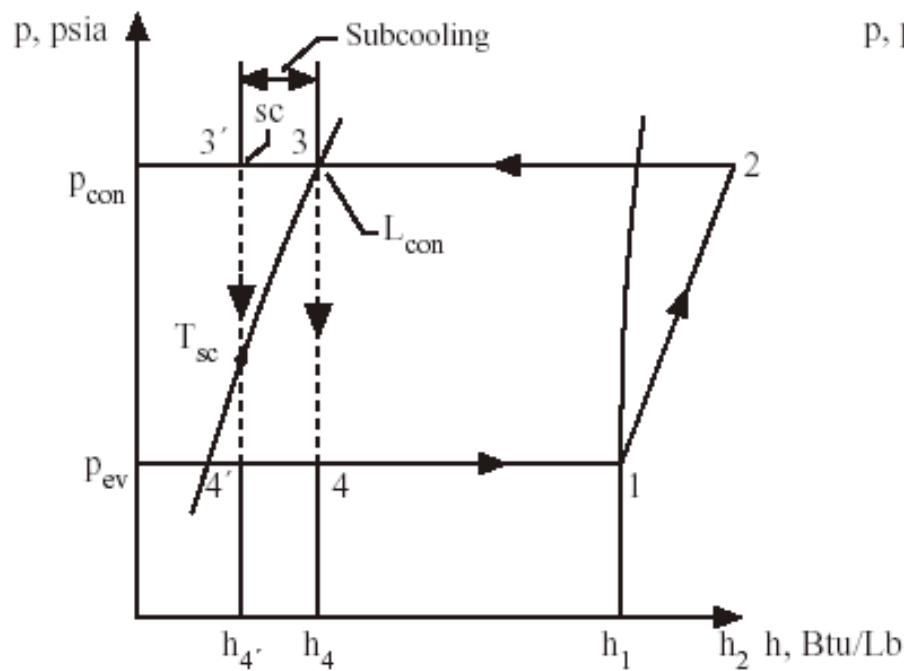




(a)



(b)



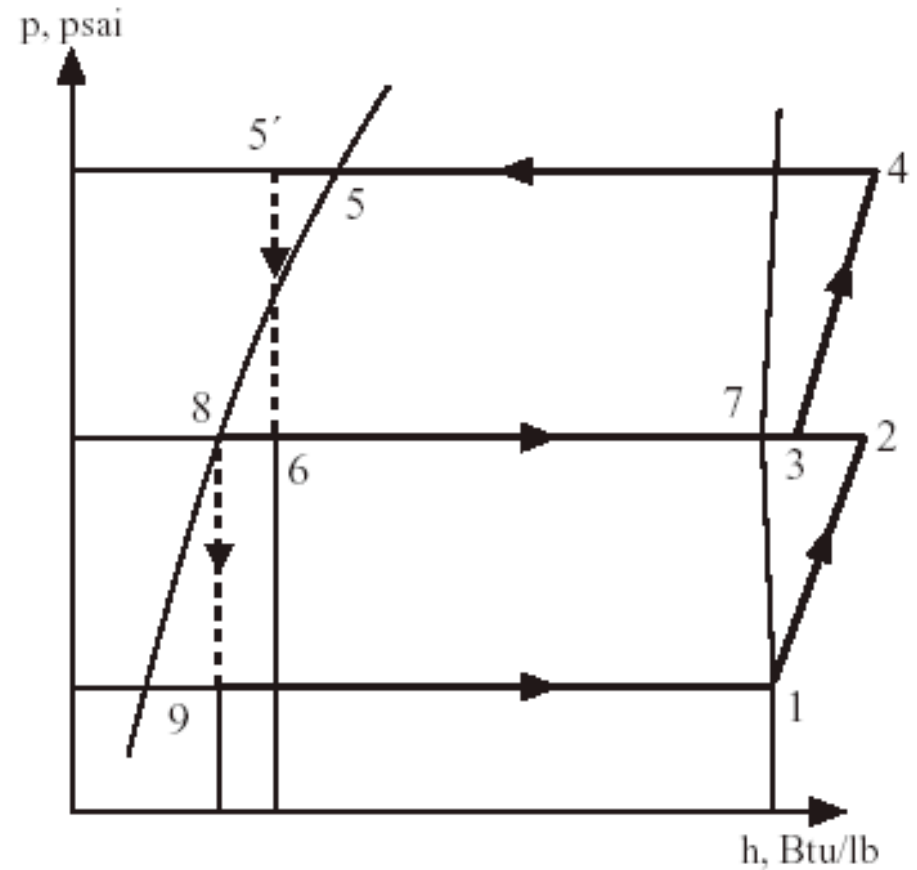
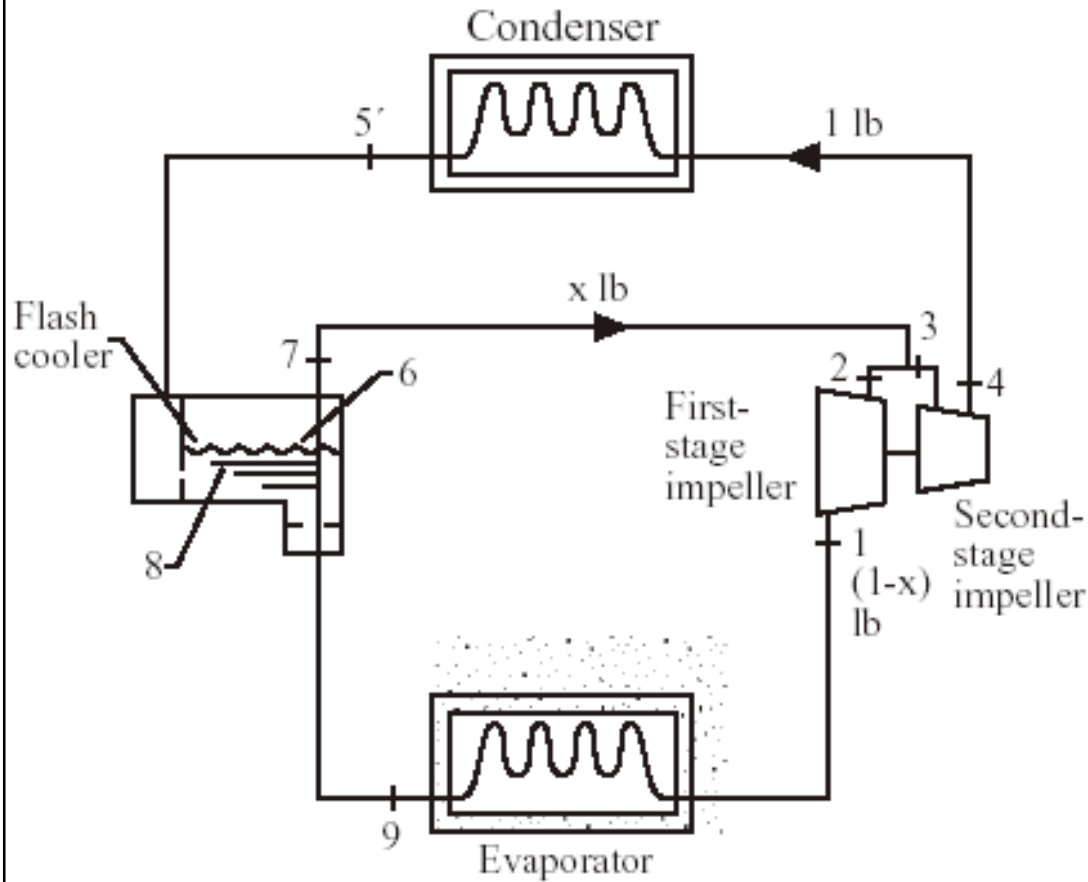


Refrigeration Cycles

- Two-stage compound systems w/ flash cooler
 - Multi-stage compression connected in series
 - Higher compression efficiency, greater refrig. effect
 - Compressor ratio
 - Flash cooler: an economizer to subcool liquid refrigerant to saturated temperature

$$\text{COP}_{ref} = \frac{q_{ref}}{W_{in}} = \frac{(1-x)(h_1 - h_9)}{(1-x)(h_2 - h_1) + (h_4 - h_3)}$$

Two-stage compound systems w/ flash cooler



* Where the ratio of suction to discharge pressure is high enough to cause a serious drop in volumetric efficiency or an unacceptably high discharge temperature, vapour compression must be carried out in two or more stages.

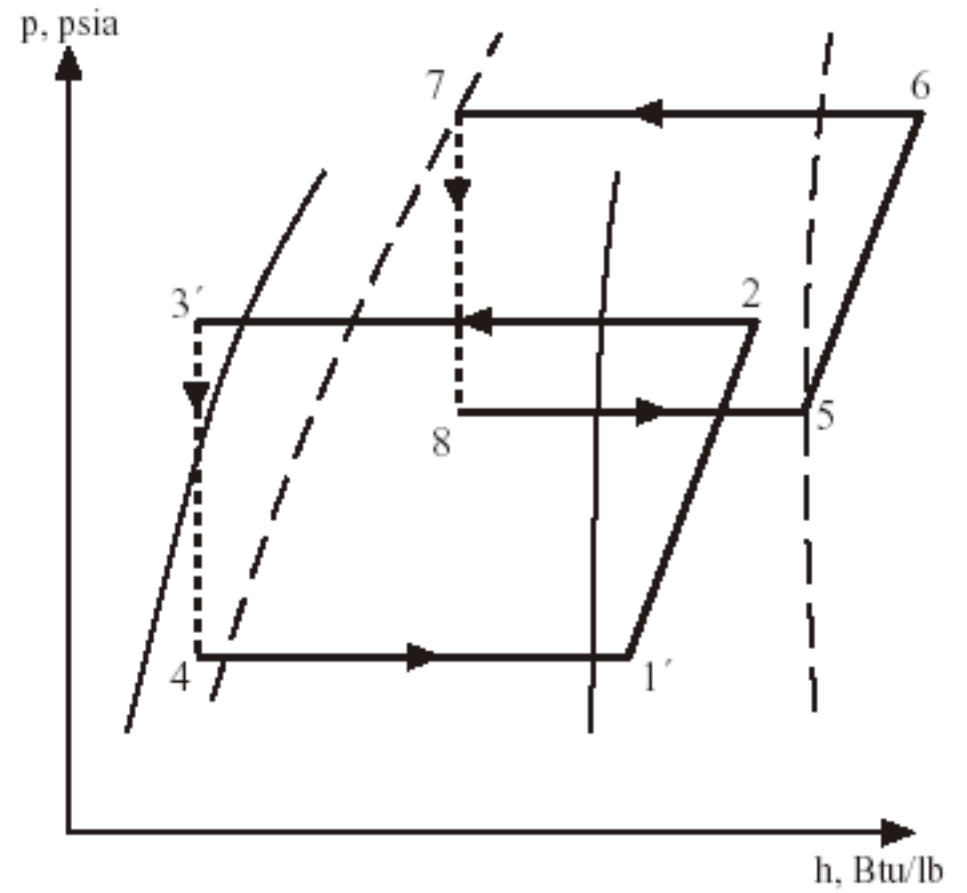
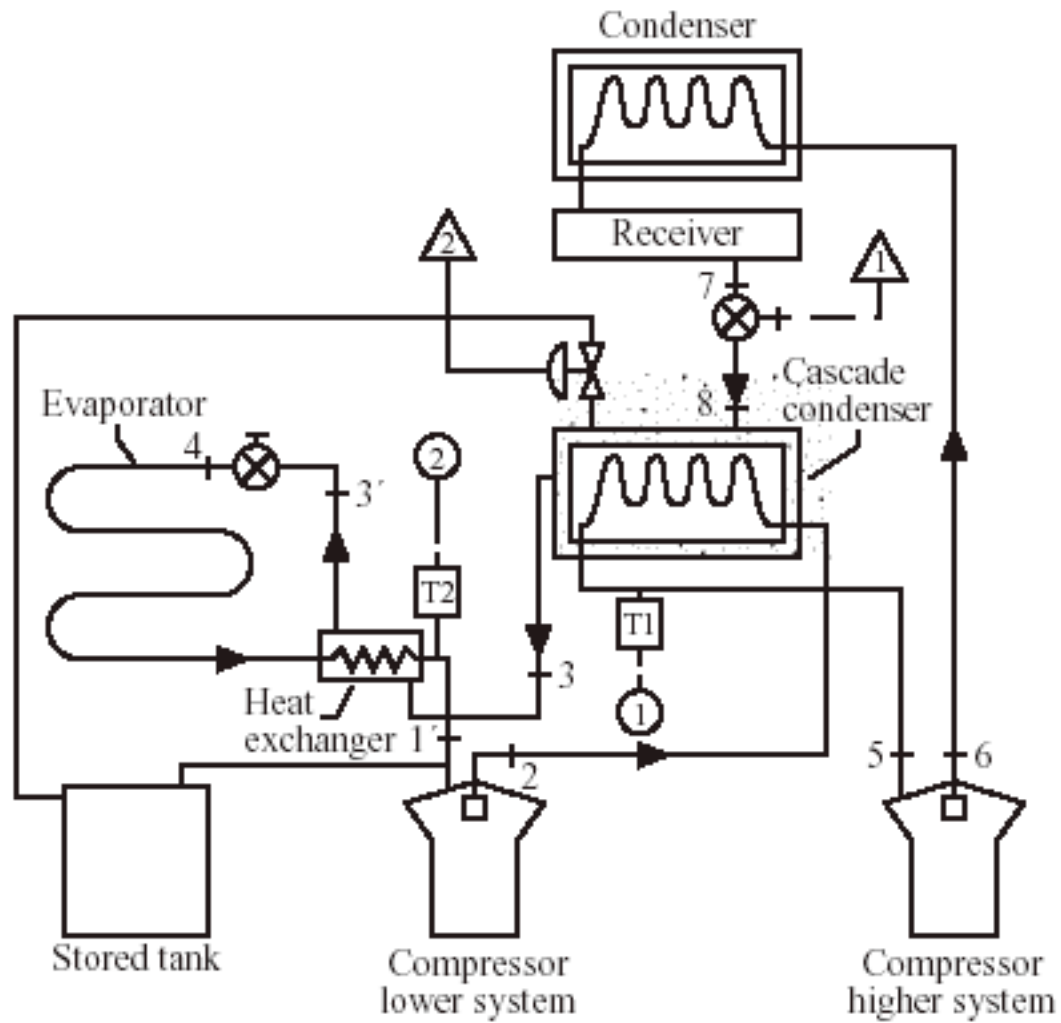


Refrigeration Cycles

- Cascade system characteristics
 - Two independently operated single-stage systems
 - Connected by a cascade condenser
 - Main advantages
 - Different refrigerants, oils and equipment can be used
 - Disadvantages: more complicated

$$\text{COP}_{ref} = \frac{q_{ref}}{W_{in}} = \frac{\dot{m}_l (h_1 - h_4)}{\dot{m}_l (h_2 - h_1) + \dot{m}_h (h_6 - h_5)}$$

Cascade system

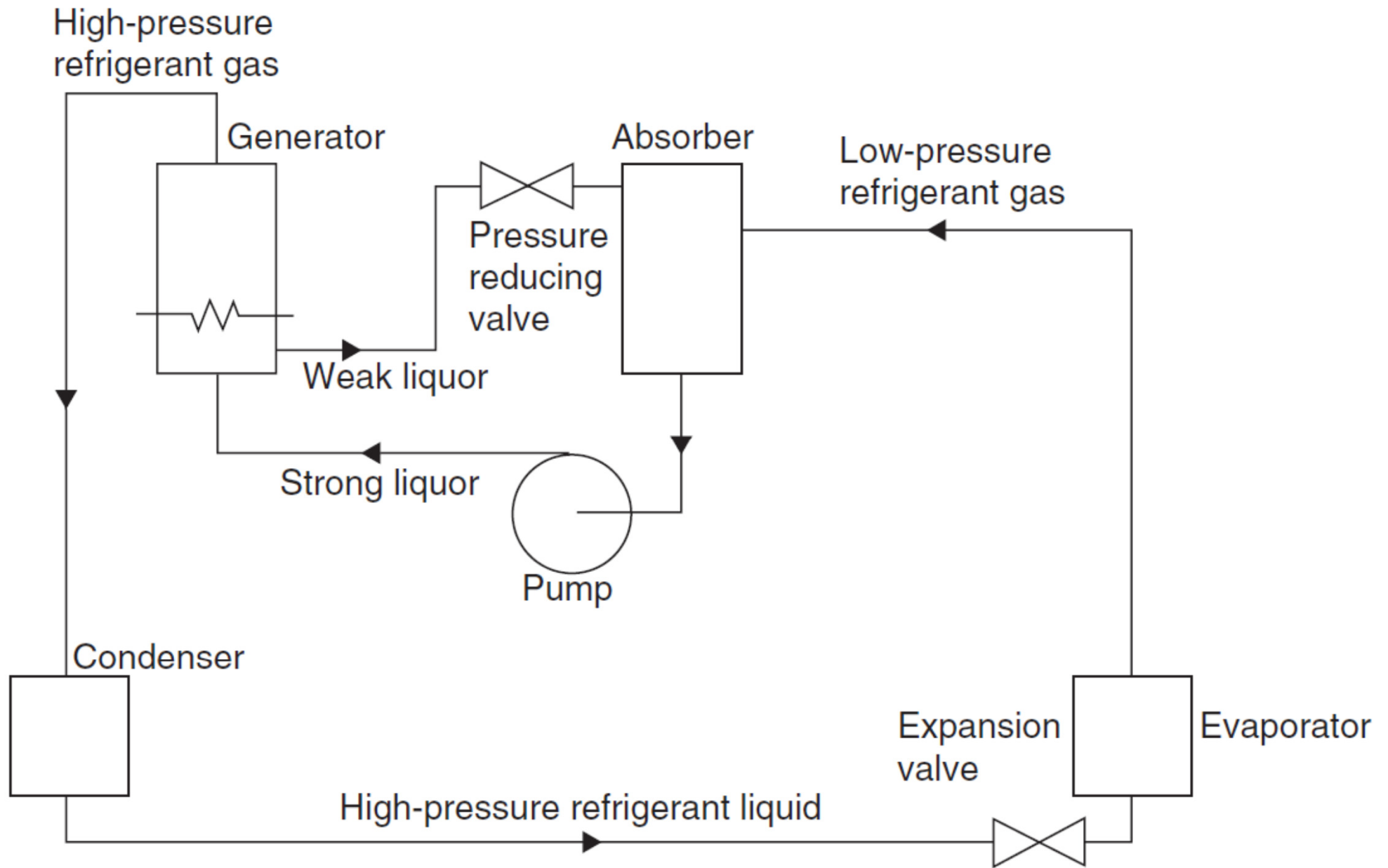


Refrigeration Cycles

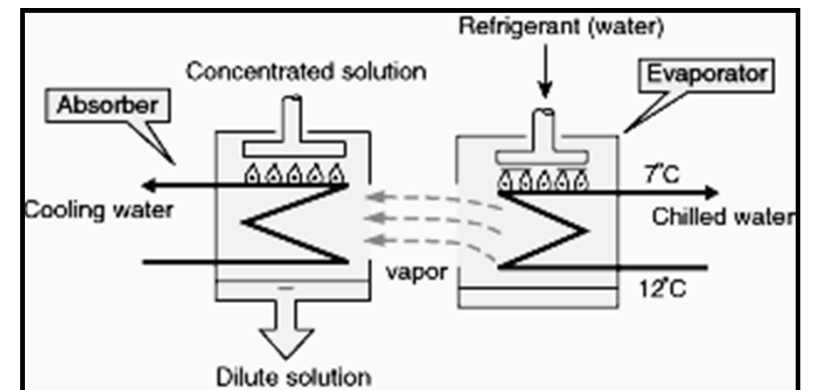
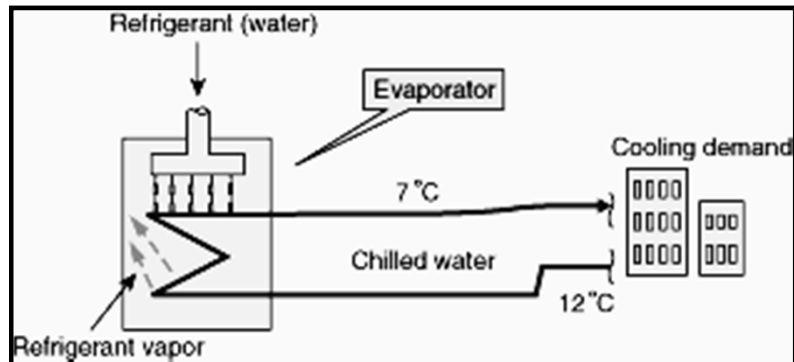
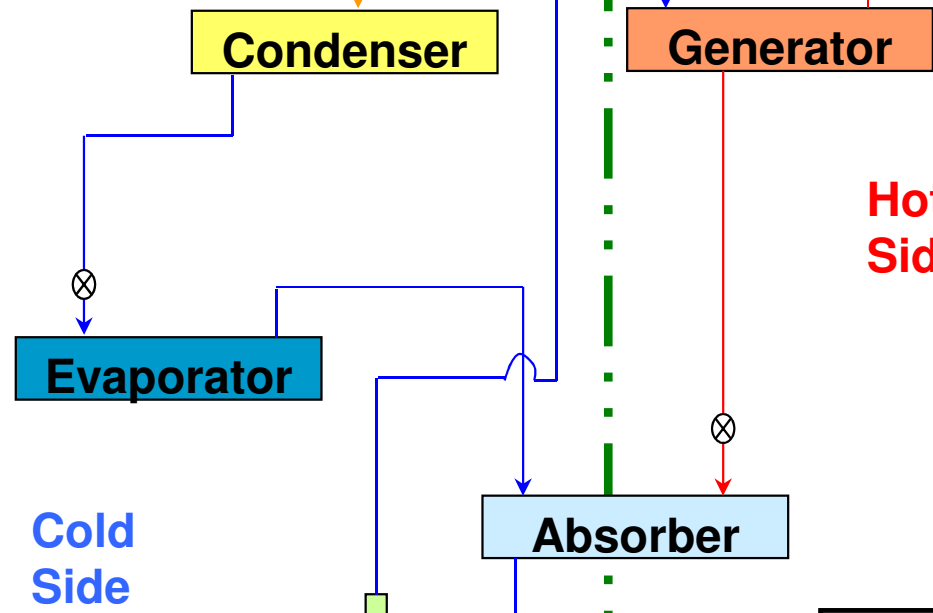
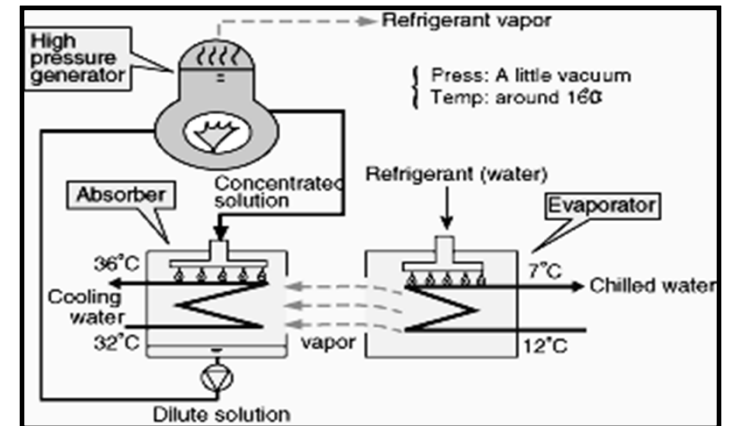
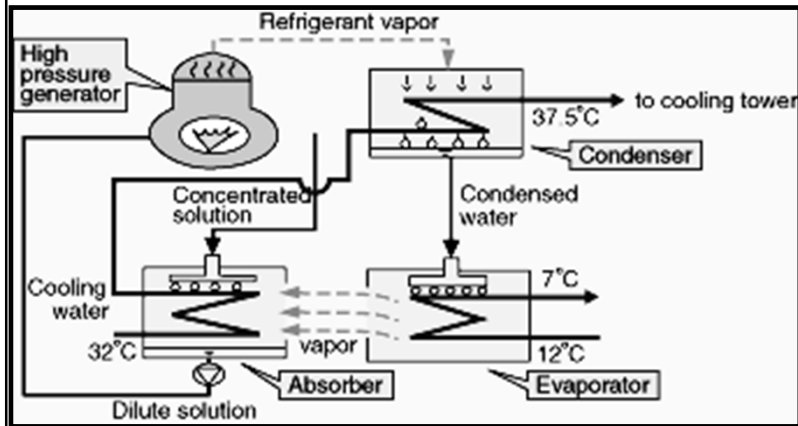


- Absorption cycle
 - Such as ammonia and lithium bromide systems
 - Absorption of ammonia gas into water, and of water vapour into lithium bromide
 - Refrigerant vapour from the evaporator is drawn into the absorber by the liquid absorbant. The liquor is then pumped up to condenser pressure and the vapour is driven off in the generator by direct heating
 - The heat energy to the generator may be any form of low-grade energy such as oil, gas, hot water or steam, or from solar radiation

Absorption cycle: basic circuit



Vapour absorption refrigeration

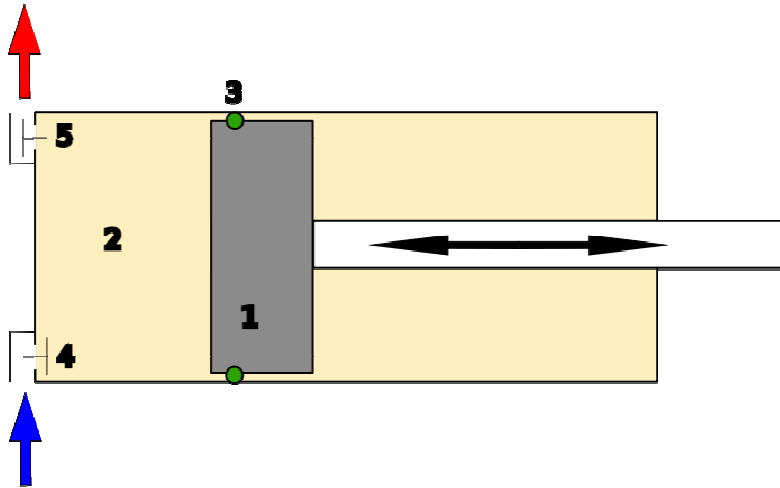




Refrigeration Systems

- Common types of compressors used in chillers (HVAC refrigeration plant):
 - Reciprocating -- piston-style, positive displacement
 - Rotary screw -- positive displacement; 2 meshing screw-rotors rotate in opposite directions
 - Scroll -- positive displacement; one spiral orbits around a second stationary spiral
 - Centrifugal -- raise the pressure by imparting velocity or dynamic energy, using a rotating impeller, and converting it to pressure energy

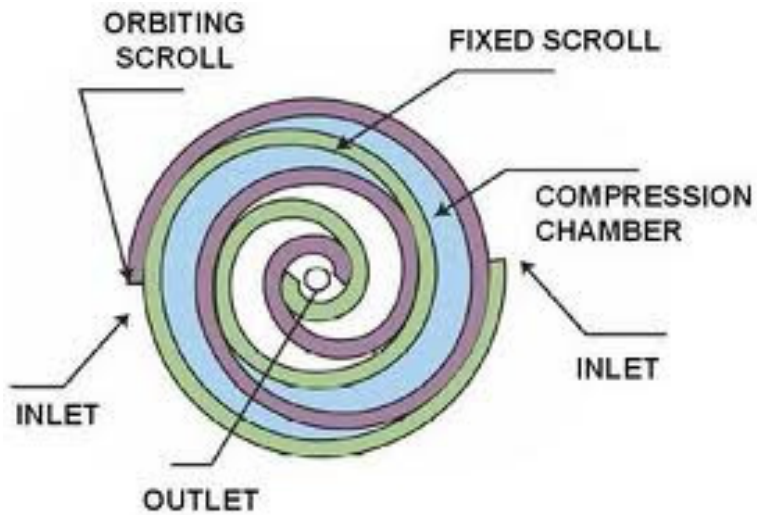
Common types of compressors used in chillers



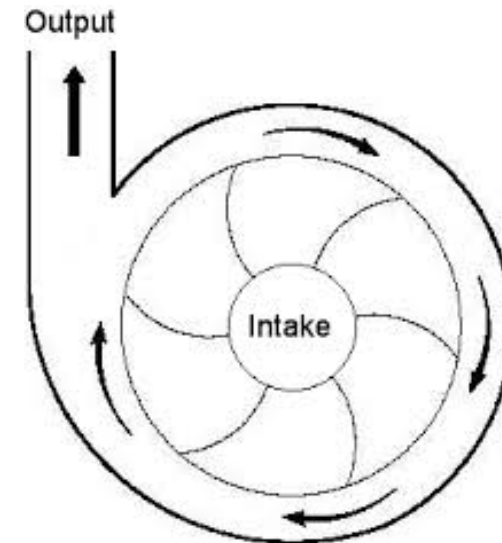
Reciprocating



Rotary screw



Scroll



Centrifugal



Refrigeration Systems

- Arrangement of compressor motor or external drive:
 - Open type
 - Hermetic (or sealed) type
 - Semi-hermetic (or semi-sealed) type





Refrigeration Systems

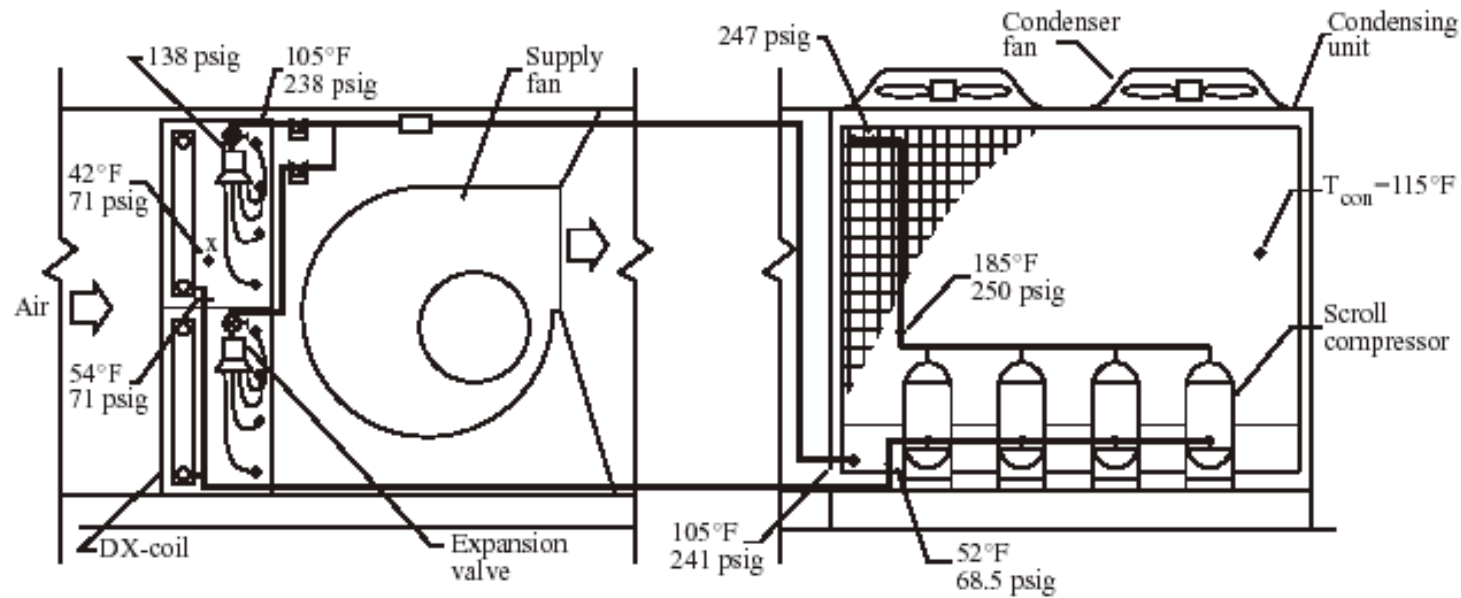
- Common refrigeration systems in HVAC
 - Direct expansion (DX) systems & heat pumps
 - Centrifugal chillers
 - Screw chillers
 - Absorption systems
- Either single-stage or multistage
- Compressor lubrication
 - Use mineral or synthetic oil
 - Use magnetic bearings (oil-free chiller/compressor)



Refrigeration Systems

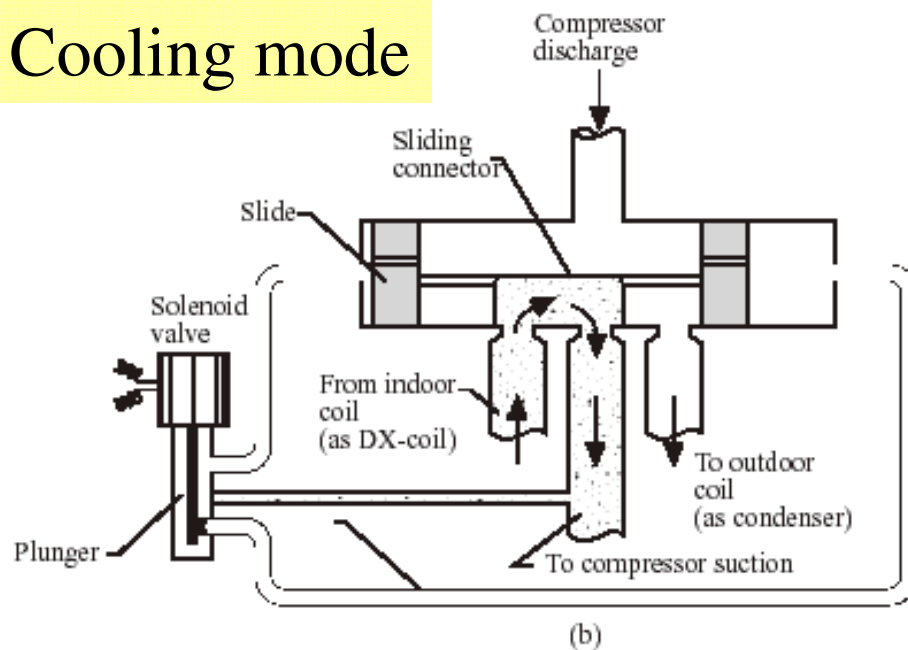
- Direct expansion (DX) systems
 - Part of the packaged air-conditioning system
 - R-22 and R-134a widely used
 - Range 3-100 TR
 - Components & accessories
 - Compressor(s): reciprocating and scroll
 - Condensers
 - Refrigeration feed
 - Oil lubrication
 - Refrigerant piping

Direct expansion (DX) system (air-cooled condenser)

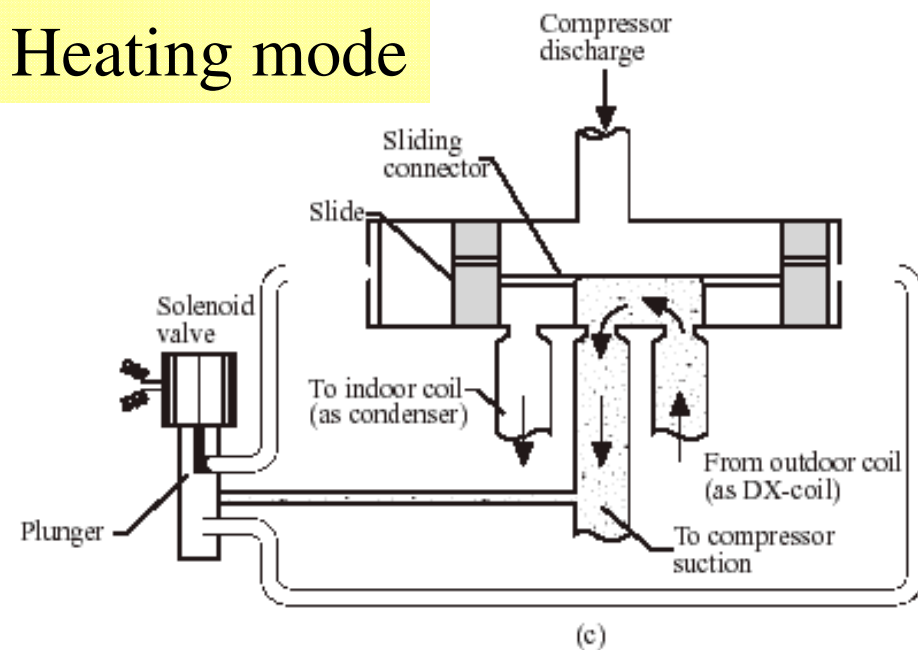


(a)

Cooling mode



Heating mode

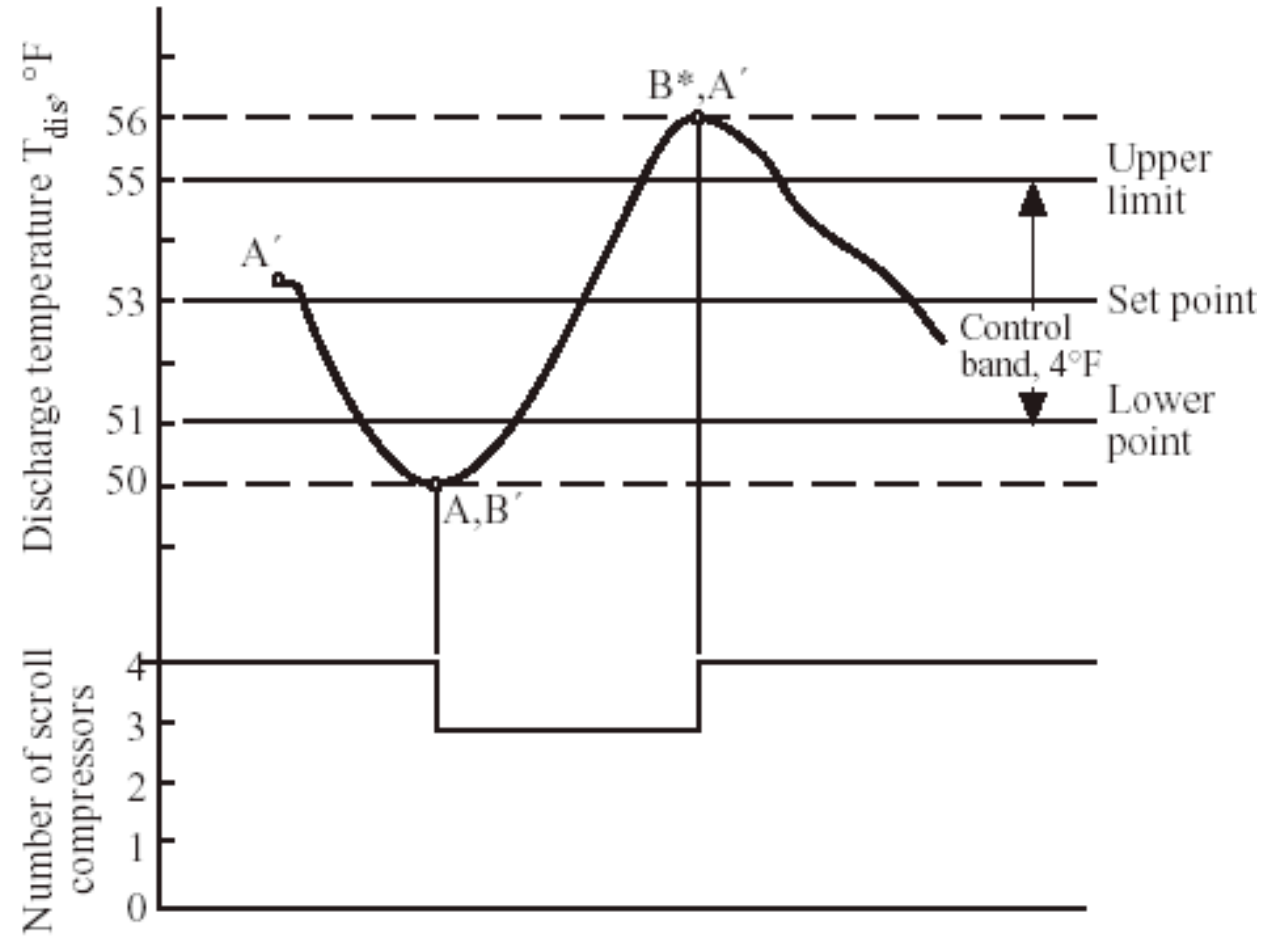
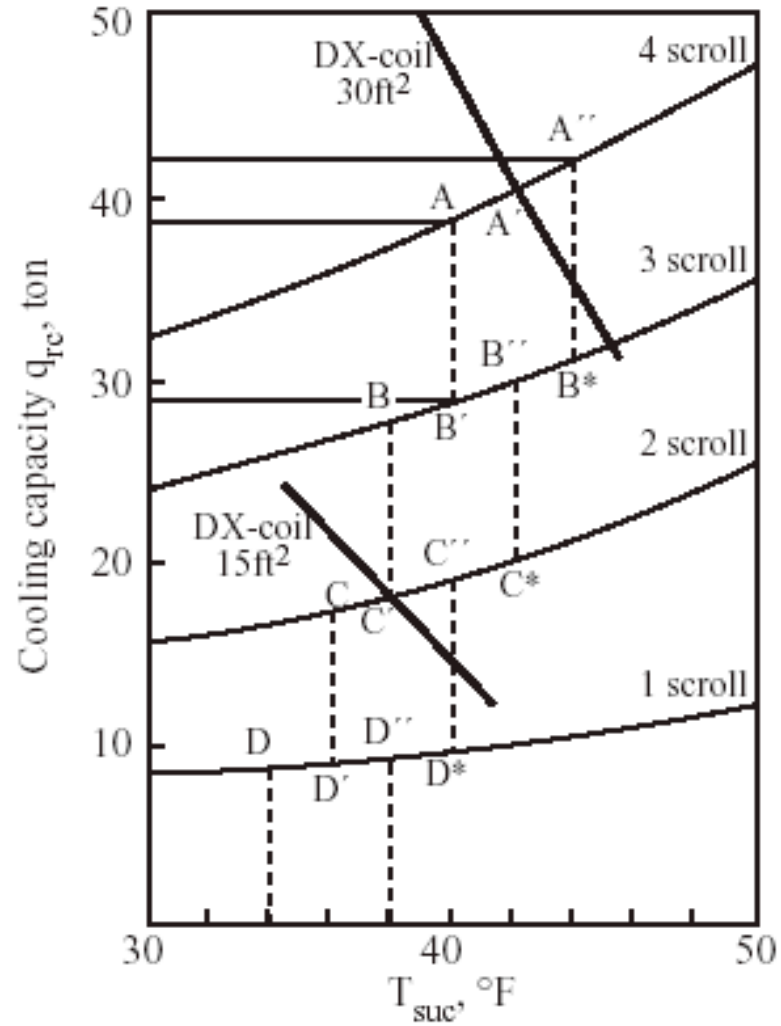




Refrigeration Systems

- Direct expansion (DX) systems (cont'd)
 - Capacity control
 - On-off control
 - Cylinder unloader
 - Speed modulation
 - Safety control
 - Low- & high-pressure control
 - Low-temperature control
 - Motor overload control
 - Pump-down control
 - Full- and part-load operation

Capacity control of a DX system





Refrigeration Systems

- Heat pumps

- Three types:

- Air-source (air-to-air)

- R-22 often used, range 1.5 to 40 TR

- Water-source

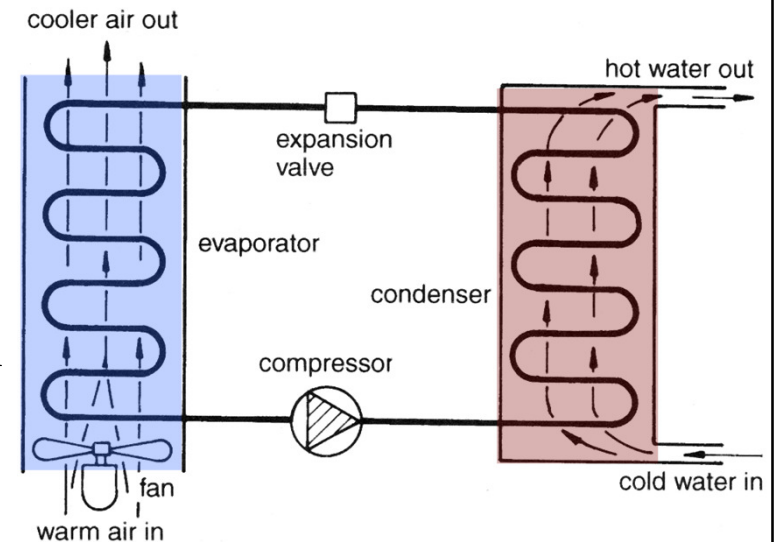
- Ground-coupled

- Extract energy from ground, water, or ambient air

- Cooling and heating mode operation

- Winter may require defrosting

- High COP & EER (energy efficiency ratio)



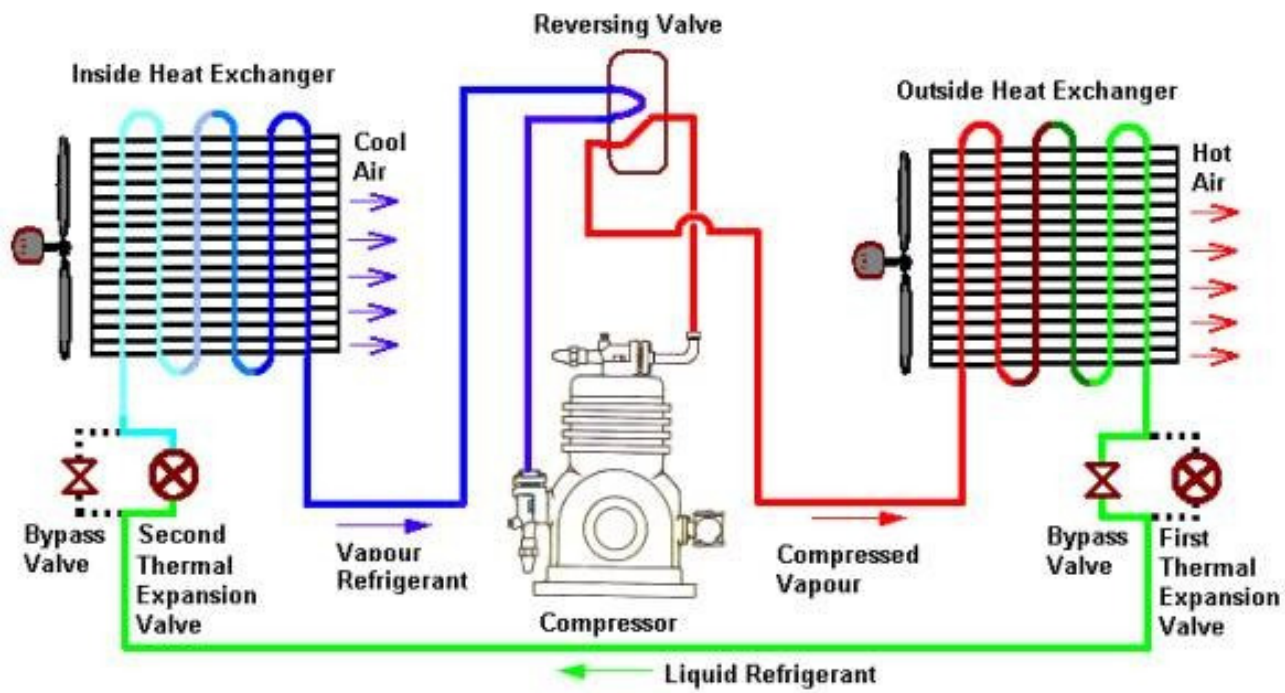


Fig. 1 - Heat Pump in Cooling Mode

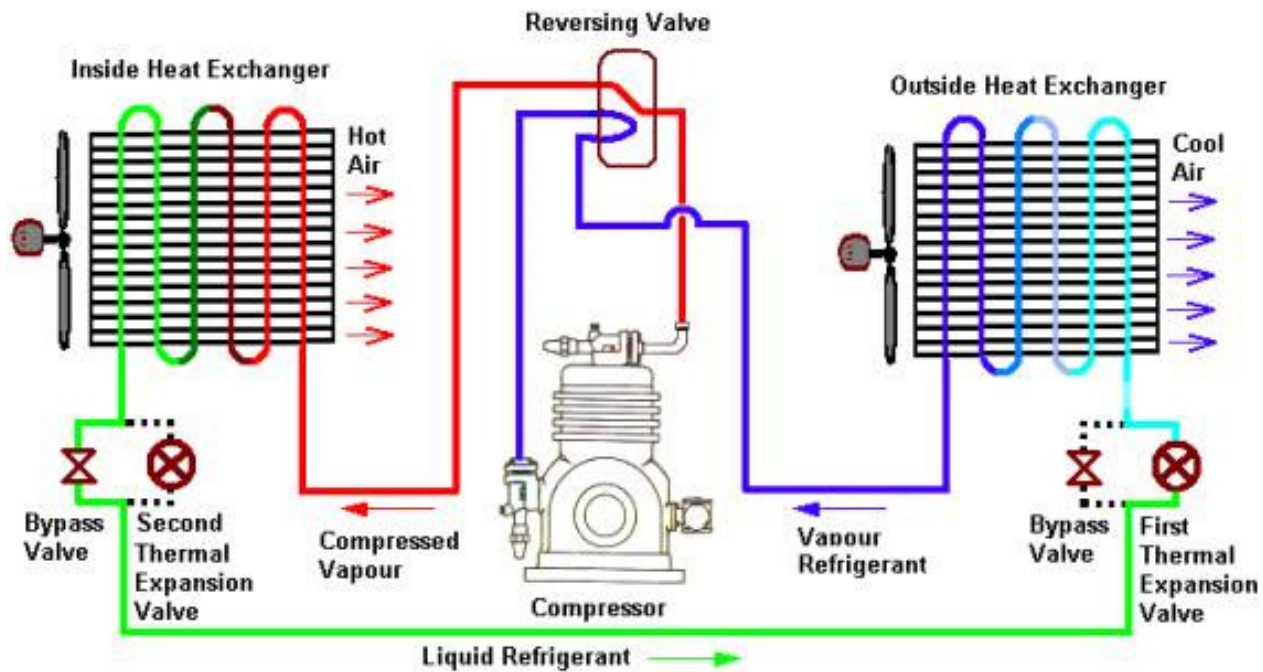


Fig. 2 - Heat Pump in Heating Mode



Refrigeration Systems

- Centrifugal chillers
 - Chiller = a refrigeration machine using a liquid cooler as an evaporator to produce chilled water
 - R-11, R-12, R-22 were used
 - R-11 replaced by R-123
 - R-12 replaced by R-134a
 - System components
 - Centrifugal compressor, evaporator, condenser, flash cooler, orifice plates & float valves, purge unit (optional)





Refrigeration Systems

- Centrifugal chillers (cont'd)
 - Performance rating: ARI Standard 550
 - COP and Integrated part-load value (IPLV)
 - Water-cooled chillers: $\text{COP} = 5$ (= 0.7 kW/TR)
 - Air-cooled chillers: $\text{COP} = 2.5$ to 2.8 (1.26-1.4 kW/TR)
 - Capacity control:
 - Inlet vanes and variable compressor speed
 - Centrifugal compressor performance map
 - Partload operation



Refrigeration Systems

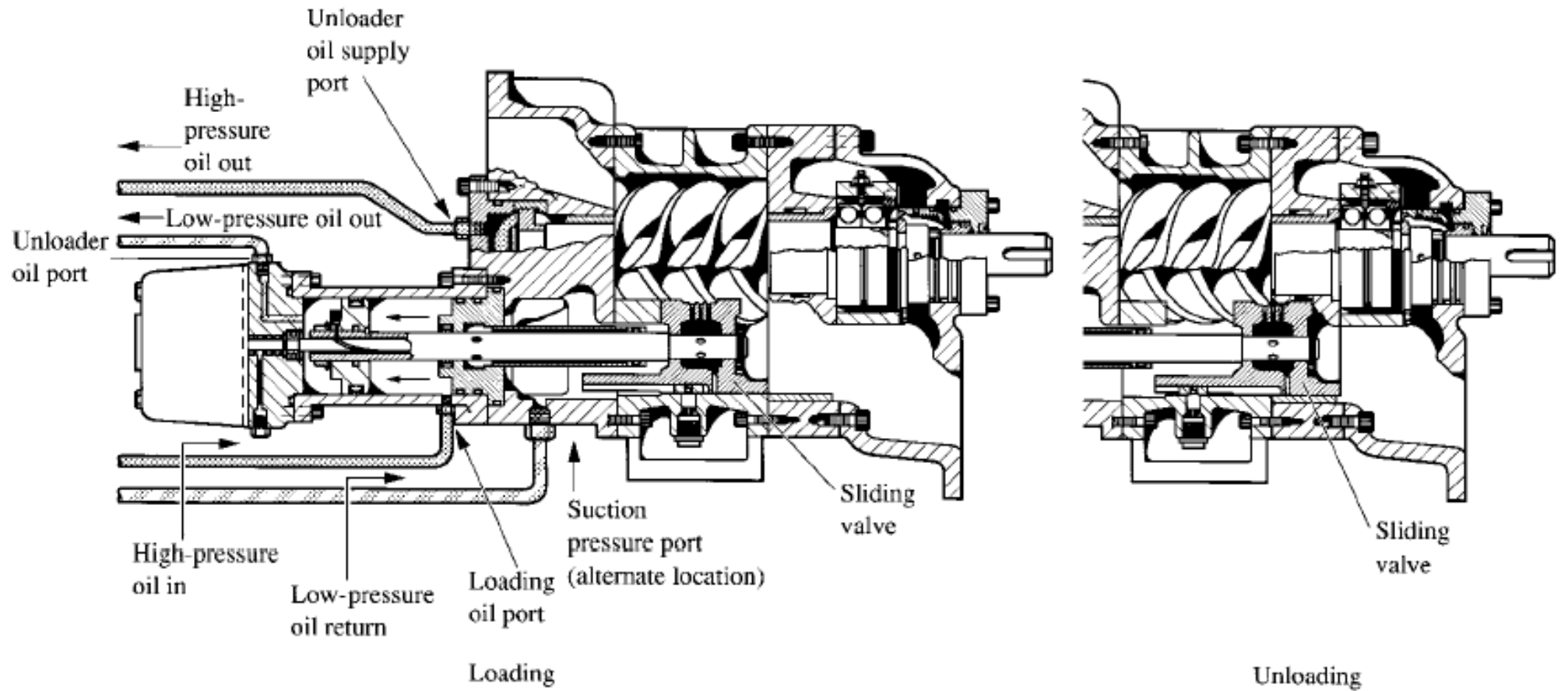
- Centrifugal chillers (cont'd)
 - Specific controls
 - Chilled water leaving temperature and reset
 - Condenser water temperature control
 - On/off of multiple chillers based on measured coil load
 - Air purge control
 - Safety controls e.g. oil pressure, freezing protection, etc.
 - Incorporating heat recovery
 - Double-bundle condenser



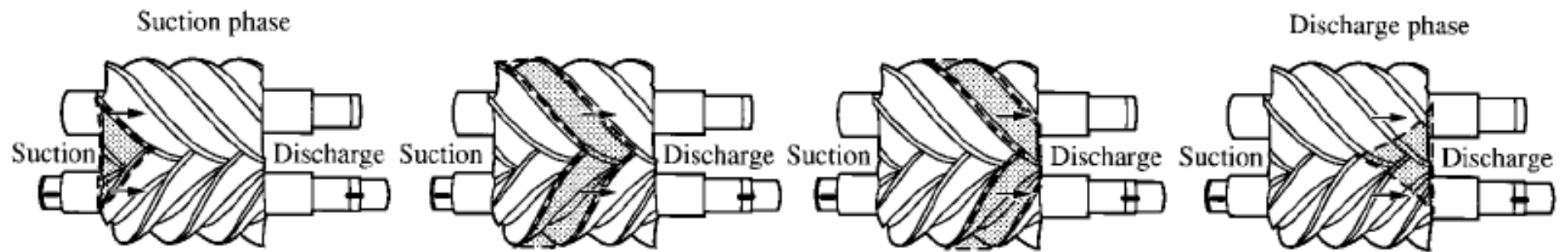
Refrigeration Systems

- Screw chillers
 - Helical rotary chiller: use screw compressor
 - Twin-screw compressors are widely used
 - Capacity 100 to 1000 TR
 - Variable volume ratio
 - Economizer
 - Similar to a two-stage compound system w/ flash cooler
 - Oil separation, oil cooling and oil injection
 - Oil slugging is not a problem

Twin-screw compressor



(a)



(b)