Chapter 10

Refrigeration & Heat Pump Cycles (Systems)

Refrigeration & Heat Pump Systems

- To maintain a region of space at a temperature blow that of the environment
- The working fluid may be (1) single phase (=> Gas Refrigeration Cycles) or (2) two phases (=> Vapor-compression-Refrigeration Cycles)
- **Refrigerator** - preservation of food

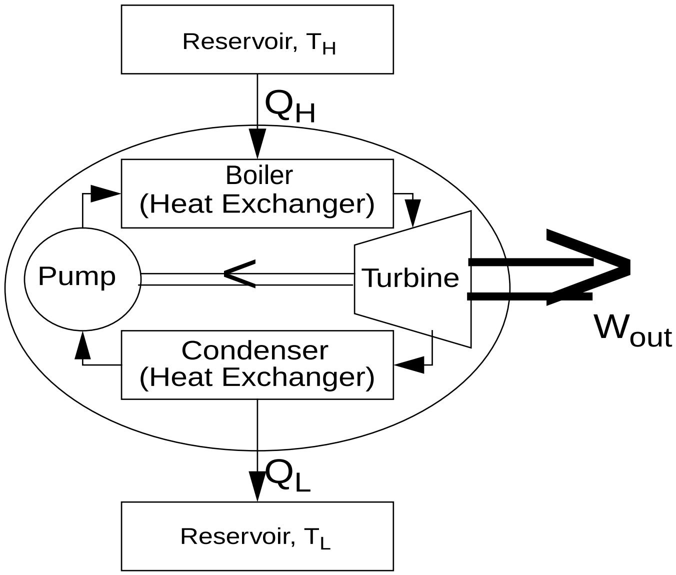
  A/C - the air conditioning of buildings (space)

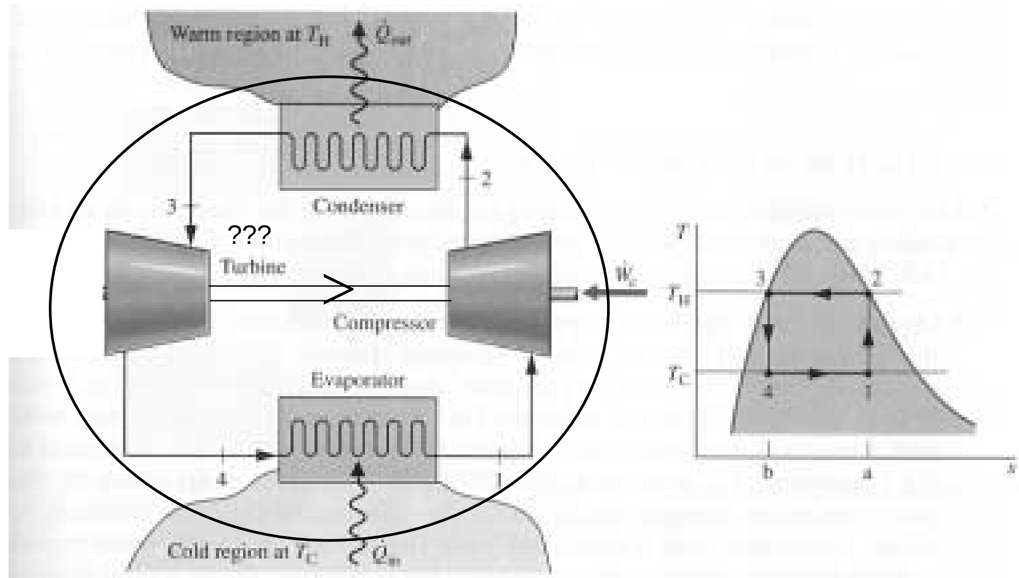
  H.P. - capable of providing both a cooling and a heating effect with the same equipment

  Liquefaction of gas (air) - liquid O_2 (e.g., for steel making), N_2 (e.g., low temperature (cryogenic)), natural gas (for shipment), liquid fuel for rocket propulsion, etc.

  Solidification of gas - e.g., dry ice

The Reversed Carnot Cycle





- 1^{st} Law: $Q_{net} = W_{net}$ and 2^{nd} Law: $Q_H/Q_L = T_H/T_L$
- For refrigerator (or A/C):

$$COP_{refrig} = \beta = \frac{Q_L}{W_{in}} = \frac{Q_L}{Q_H - Q_L} > 0$$

$$\beta_{max} \geq \beta$$

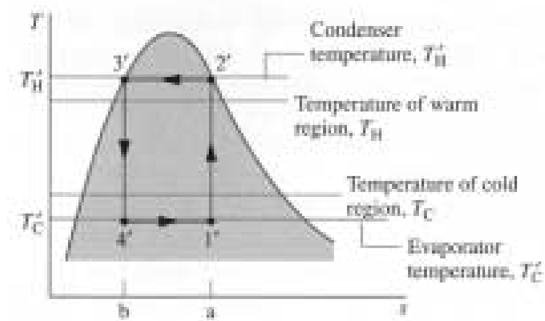
$$COP_{refrig,\,Carnot} = \beta_{max} = \frac{T_L}{T_H - T_L} > 0$$

- Discussions:

(1) T_H can not be less than the temperature of the environment to which heat is rejected.

(2) T_L can not be greater than the temperature of the cold region from which heat is removed.

(3) The reversed Carnot Cycle is not practical due to



(a) processes 2->3 (condenser, T_H) & 4->1 (evaporator, T_L): must have $\Delta T \approx 10^0$C for proper heat transfer

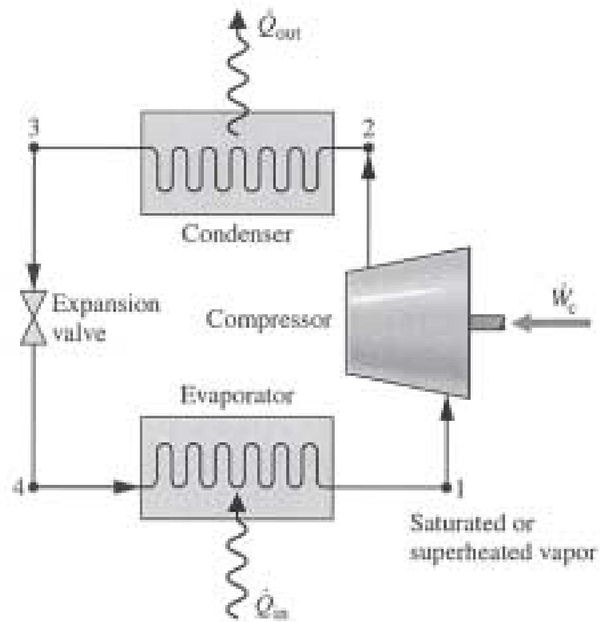
(b) process 1->2 (compressor): 2-phase region

(c) processes 2->3 & 4->1: if T = constant => must be in 2-phase region => hard to keep constant T process in reality => P = C.

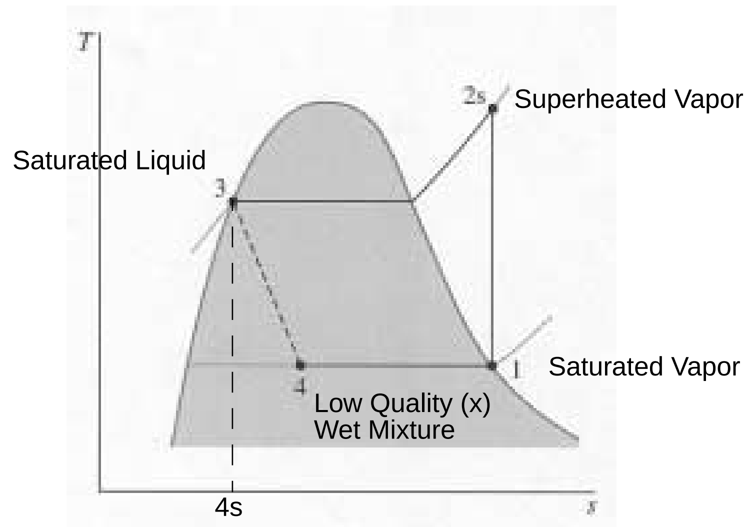
(d) process 3->4 (turbine? or else?) => 2-phase region, if turbine => corrosion and efficiency issues => throttling devices, e.g., expansion valve, capillary tube, etc.

(Ideal) Vapor-Compression Refrigeration Cycle

VCR System



Ideal VCR Cycle



- **IDEAL** VCR Cycle: 1->2s s = C Compression
  2s->3 P = C Heat Removal
  3->4 h = C Expansion
  4->1 P = C Heat Addition

NOTE: All processes are reversible expect 3->4, which is adiabatic but irreversible => $h_3 = h_4$

- Discussions:

(1) System Analysis:

$$q_{41} = h_1 - h_4 \ \ (\ \Rightarrow q_{in}) \qquad q_{23} = h_3 - h_2 \ \ (\ \Rightarrow -q_{out})$$

$$w_{12} = h_2 - h_1 \ \ (\ \Rightarrow w_{in}) \qquad h_3 = h_4$$

$$\beta = \frac{q_{in}}{w_{in}} = \frac{h_1 - h_4}{h_2 - h_1}$$

(2) For Ideal Cycle:

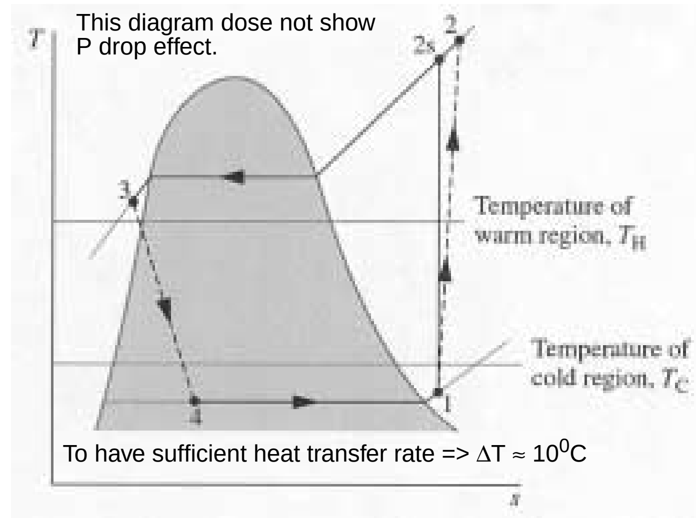
$$h_1 = h_g(\text{at } P = P_L) \qquad h_2 = h(\text{at } P = P_H \ \& \ s_2 = s_1)$$

$$h_3 = h_f(\text{at } P = P_H) \qquad h_3 = h_4$$

(3) The rate of refrigeration systems is frequently given on the basis of the **tons** of refrigeration provided by the unit operating at design conditions

1 ton => heat-removal rate from the cold region (or the heat-absorption rate by the fluid passing through the evaporator) of 211 kJ/min or 200 Btu/min.

(4) **Deviation of the actual VCR Cycle from the ideal cycle**: Primarily due to (a) pressure drops associated with fluid flow and (b) heat transfer to or from the surroundings



(5) The actual cycle might approach the one shown:

(a) State 1 might be in SH region: This represents an overdesign to ensure that the compressor is always handling the vapor phase (it's difficult to design state 1 = saturated vapor). This will increase the size of evaporator. This represents a loss because the compressor needs more work due to *v* is larger in SH than x=1 $(w = \int v dP)$.

(b) 1->2 (not 2s): due to irreversibility

(c) Heat transfer from compressor to/from surrounding (T_H) will also affect the compressor performance.

(d) State 3, in general, is in the subcooled region. This is a beneficial effect, since low h_3 => low h_4 => larger energy can be removed by the evaporator. However, this will also increase the size of the condenser.

(e) $\eta_c = \frac{(w_c)_s}{w_c} = \frac{h_{2s} - h_1}{h_2 - h_1}$

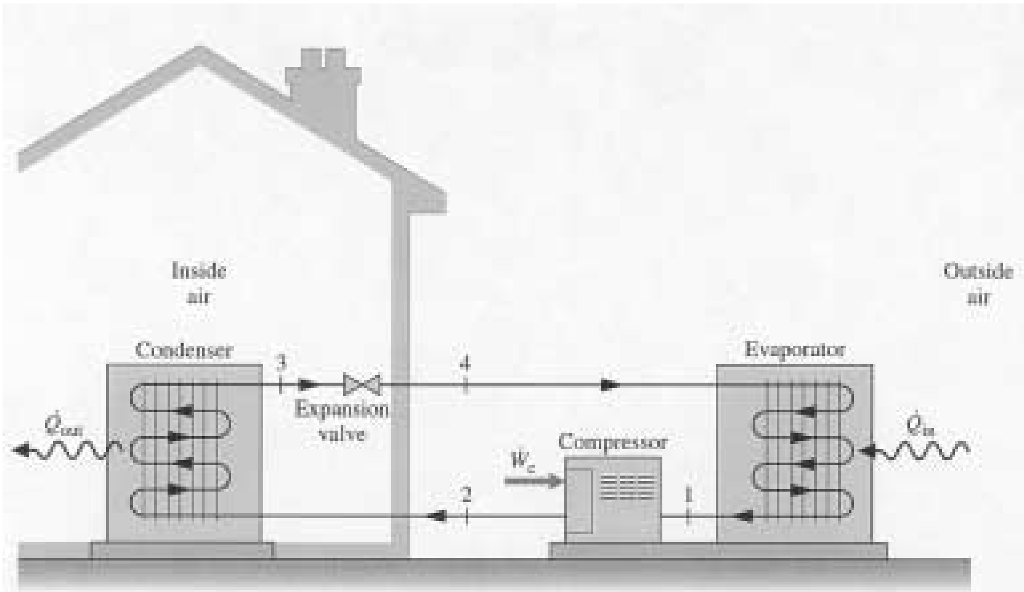
Design Considerations

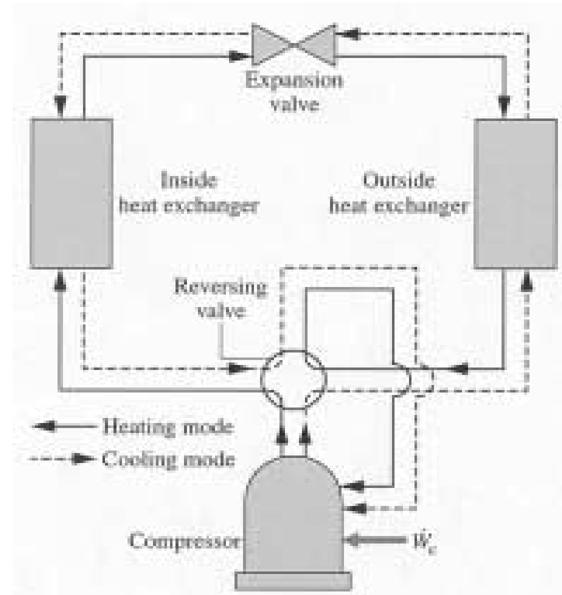
- The two desired saturation temperatures ($T_{condenser}$ and $T_{evaporator}$) determine the operating pressures ($P_{condenser}$ and $P_{evaporator}$)
- P_{evap} should be > 1 atm. to avoid leakage into the equipment.
- P_{cond} should not be over 10 to 15 bars ($T_{R\text{-}134a,\ sat}$: 39.39 to 55.18^{0}C)
- The refrigerant needs to be nontoxic, non-corrosiveness, chemically stable, low-cost, have a relatively high enthalpy of vaporization, environmentally friendly, etc.
- Due to the range of applicability of VCR systems, no one fluid is suitable for all cases.
  - (a) Early days - Ammonia, Sulfur Dioxide, ethyl.
  - (b) 1930s to mid-80s - CFCs (ChloroFluoroCarbons), e.g., R-11, R-12, R-22, and R-502 (a blend of R-22 and R-115).
  - (c) Late-80s to present - HFCs (HydroFluoroCarbons), such as R-134a.
- Two important considerations in selecting a refrigerant:
  - (a) Temperature at which refrigeration is desired (or heating in the case of heat pump).

(b) the type of equipment to be used.

- Since the refrigerant undergoes a phase change during the heat transfer process (condenser and evaporator), the pressure of the refrigerant will be the saturation pressure during these process. Accordingly,
  (a) Low pressure => large specific volume refrigerant => large equipment
  (b) High pressure => smaller equipment, but must be designed to withstand higher pressure.
- The type of compressor used has a particular bearing on the refrigerant:
  (a) Reciprocating compressors are best adapted to low specific volume refrigerant, i.e., high pressure.
  (b) Centrifugal compressors are best adapted to high specific volume refrigerant, i.e., low pressure.
- For extremely low temperature applications:
  (a) a binary fluid system may be used by cascading two separating systems, or
  (b) a single fluid system may be operated using a two-stage compressor, in which only part of the working fluid is expanded to the lowest-temperation portion of the refrigeration cycle.
- Text book example

Heat Pump (Heating & Cooling) Systems





$$\beta = COP_{HP,\,cool} = \frac{Q_L}{W_{in}} = \frac{h_1 - h_4}{h_2 - h_1}$$

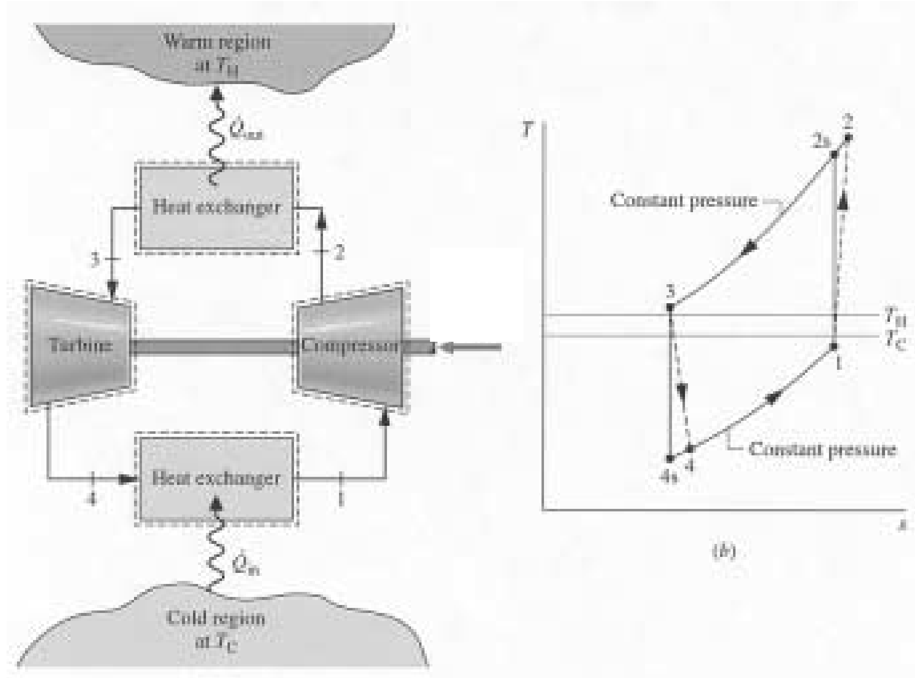
$$\gamma = COP_{HP,\,heat} = \frac{Q_H}{W_{in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

$$\gamma_{max} = COP_{HP,\,Carnot} = \frac{T_H}{T_H - T_L}$$

- Text book example

Gas (Air-Standard) Refrigeration Systems

- A Reversed Brayton Cycle
- No phase change, only gas phase.
- Its main use in practice is in the liquefaction of air and other gases and in certain special situations that require refrigerations, such as aircraft cabin cooling (open cycle).



- Cycle Analysis:

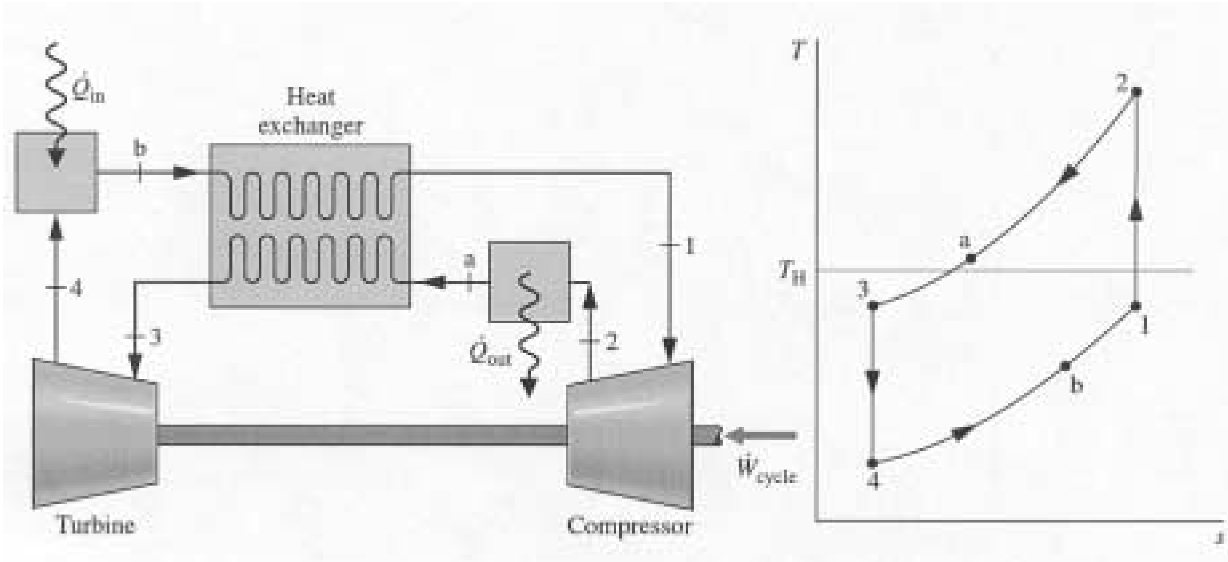
$$w_c = h_1 - h_2 \qquad w_t = h_3 - h_4 \qquad q_{41} = h_1 - h_4$$

$$\beta = \frac{q_L(= q_{41})}{w_{cycle}(= -(w_c + w_t))} = \frac{h_1 - h_4}{(h_2 - h_1) - (h_3 - h_4)}$$

- **NOTE**: $T_3 > T_H > T_1$ ==> Gas-Refrigeration Cycle with Internal Regenerator

- Text book example

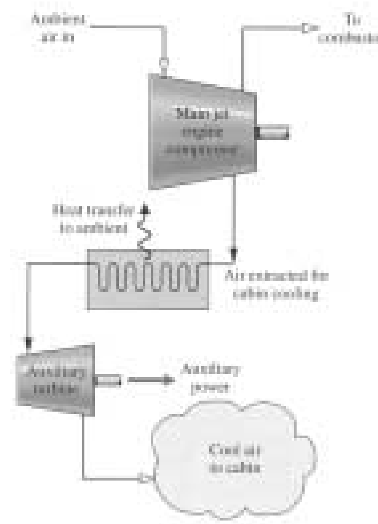
Gas Refrigeration Cycle with Regenerator



- Aircraft cabin cooling application
- If T_3 can be reduced => T_4 can be reduced too

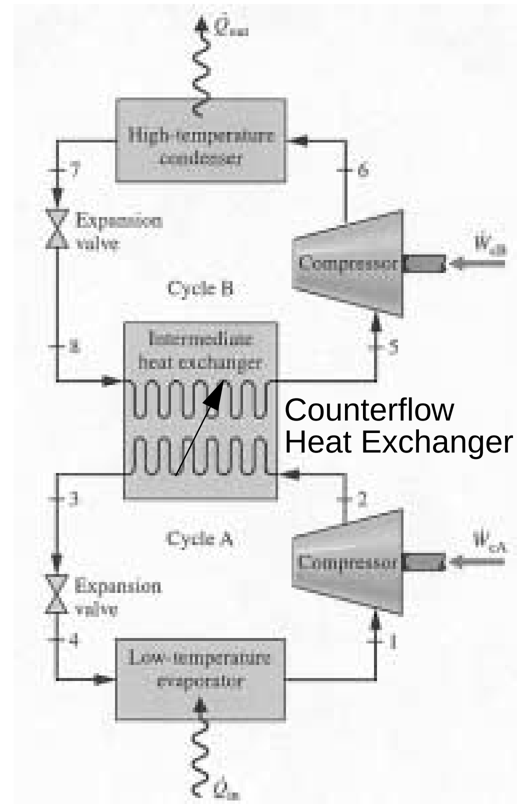
  => extremely low temperature can be achieved

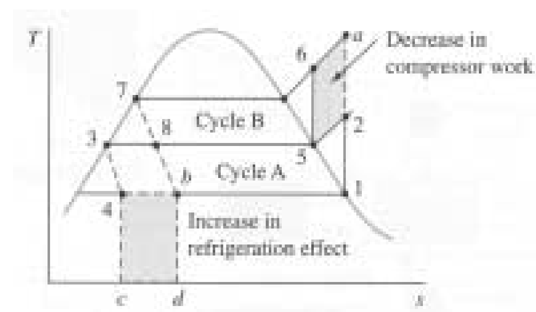
  => such use of heat exchangers internal to the cycle is important in process for liquefaction of gases.



Cascade VCR System

- For large $\Delta T = T_{consenser} - T_{evaporator}$, i.e., to achieve extremely low temperature application => liquefaction and solidification.
- Cascade => VCR systems in SERIES such that the condenser of a low-temperature cycle provides the heat input to the evaporator of a high-temperature cycle, e.g., 2 units in series
- Normally a different refrigerant would be used in each separate cycle, in order to match the desired ranges of T & P.
- The Ts diagram shows an ideal double-cascade system using the same refrigerant in each loop.
- If two different refrigerants => two separate Ts diagrams must be used.
- Note: Normally $\dot{m}_B \neq \dot{m}_A$, they are fixed by





$$\dot{m}_A(h_2 - h_3) = \dot{m}_B(h_5 - h_8)$$

if the overall heat exchange is well insulated.

- If a single refrigeration cycle could be used for the overall temperature range, this would be represented by the cycle 1->a->7->b->1.
- Two significant effects are apparent from the Ts diagram:

  (1) for the single cycle - the compressor work is increase by

  area 2->a->6->5->2.

  (2) there is a decrease in the refrigeration capacity when a single unit is used => 4->b->d->c->4.

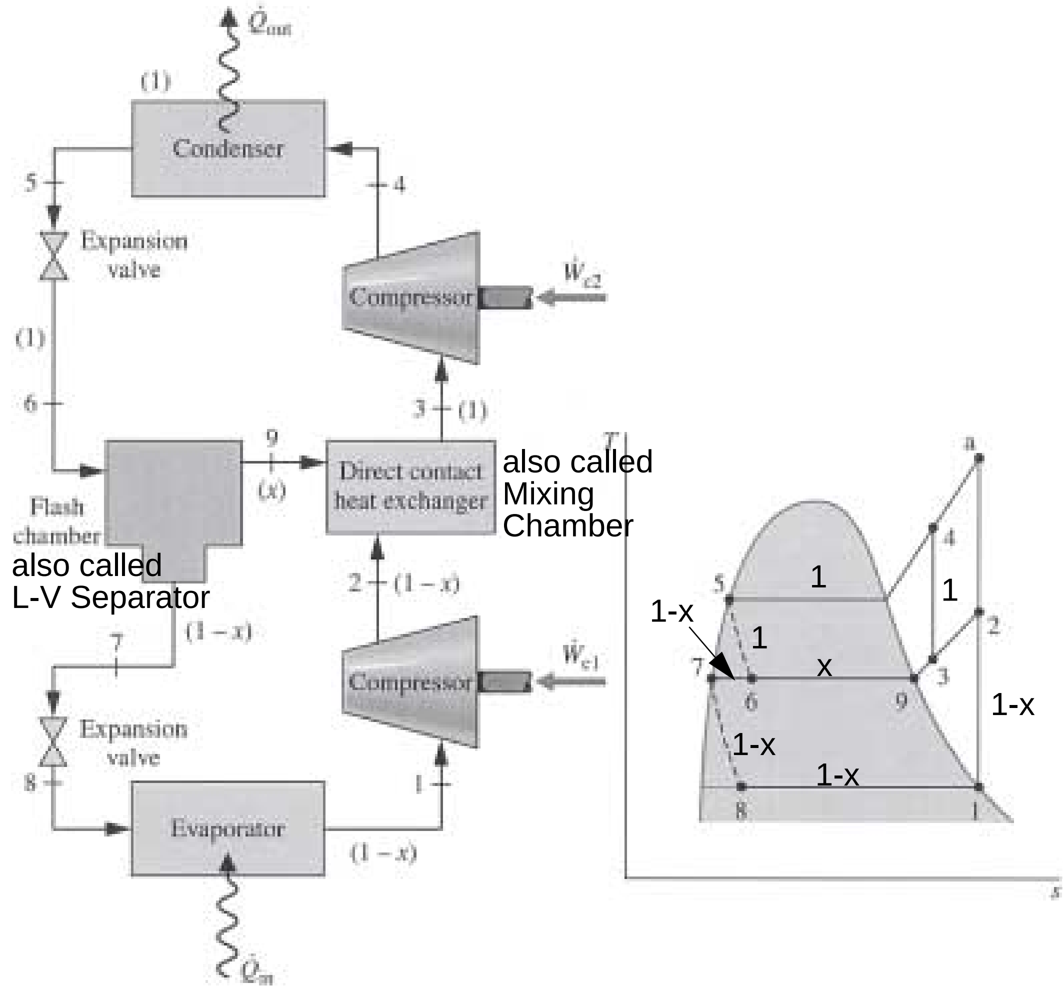
- For the double-cascade system shown, it is important that the triple-state temperature of the fluid in cycle B be lower than the critical temperature of the fluid in cycle A.
- Can have more than 2 units, if needed.

Multistage Compression with Intercooling VCR System

- To reduce the required compressor work input.
- Idea:

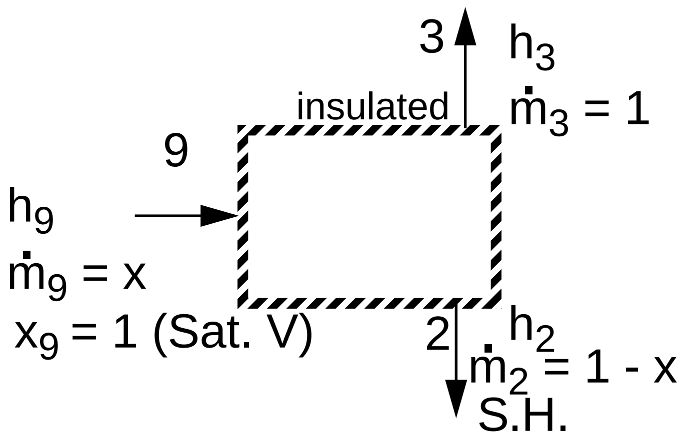
  For gas power cycles, the heat removed from the intercooler is usually transfer to the environment.

  For refrigeration cycle, the sink for the energy can be the circulating refrigerant itself, because in many sections of the cycle, the temperature of the refrigerant is below the environmental temp.



- How to fix state 3 (already know $p_3 = p_2$, need one more):

  if $\dot{m}$ through states 3->4->5->6 is "1" and the fraction of vapor formed in the flash chamber has the quality "x" at state 6, then for the mixing chamber:



$$h_3 = (1-x)h_2 + xh_9$$

- COP:

$$\dot{Q}_{refrig} = (1-x)(h_1 - h_8)$$

$$\dot{W}_C = (1-x)(h_2 - h_1) + (h_4 - h_3)$$

$$COP = \frac{\dot{Q}_{refrig}}{\dot{W}_C}$$

Absorption Refrigeration System

- Recall

  $W_{pump, liquid} << W_{compressor,vapor}$

- ARS => use pump not compressor

  => need absorber to absorb the refrigerant vapor to form a *liquid solution* before going through the pump.

  => to retrieve the refrigerant vapor from the *liquid solution* before entering the condenser => need generator, i.e., high temperature source

  Generator sources: solar, geothermal, fuel, etc.