TOPIC 5

REFRIGERATION CYCLES

Definition

- Refrigeration is the process of removing heat from an enclosed space, or from a substance, and rejecting it to an environment.
- The primary purpose of refrigeration is lowering the temperature of the enclosed space or substance and then maintaining that lower temperature.
- The term cooling refers generally to any natural or artificial process by which heat is dissipated. The process of artificially producing extreme cold temperatures is referred to as cryogenics.

Methods of Refrigeration

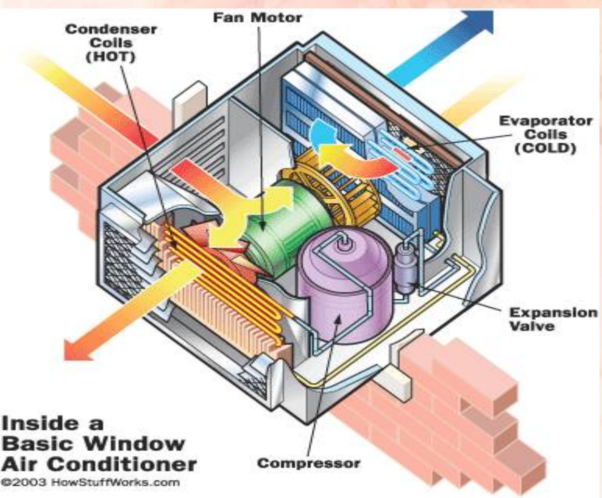
- **Methods of refrigeration can be classified as *non-cyclic*, *cyclic* and *thermoelectric*.**
- **Non-cyclic refrigeration -** cooling is accomplished by melting ice or by subliming dry ice (frozen carbon dioxide). Are used for small-scale refrigeration i.e. laboratories and workshops, or in portable coolers.
- **Cyclic refrigeration -** Consists of a refrigeration cycle, heat is removed from a low-temperature space/source and rejected to a high-temperature sink with the help of external work
- Cyclic refrigeration can be classified as **Vapor cycle** and Gas cycle
- Vapor cycle refrigeration can further be classified as:
  - **Vapor-compression refrigeration**
  - Vapor-absorption refrigeration

Methods of Refrigeration

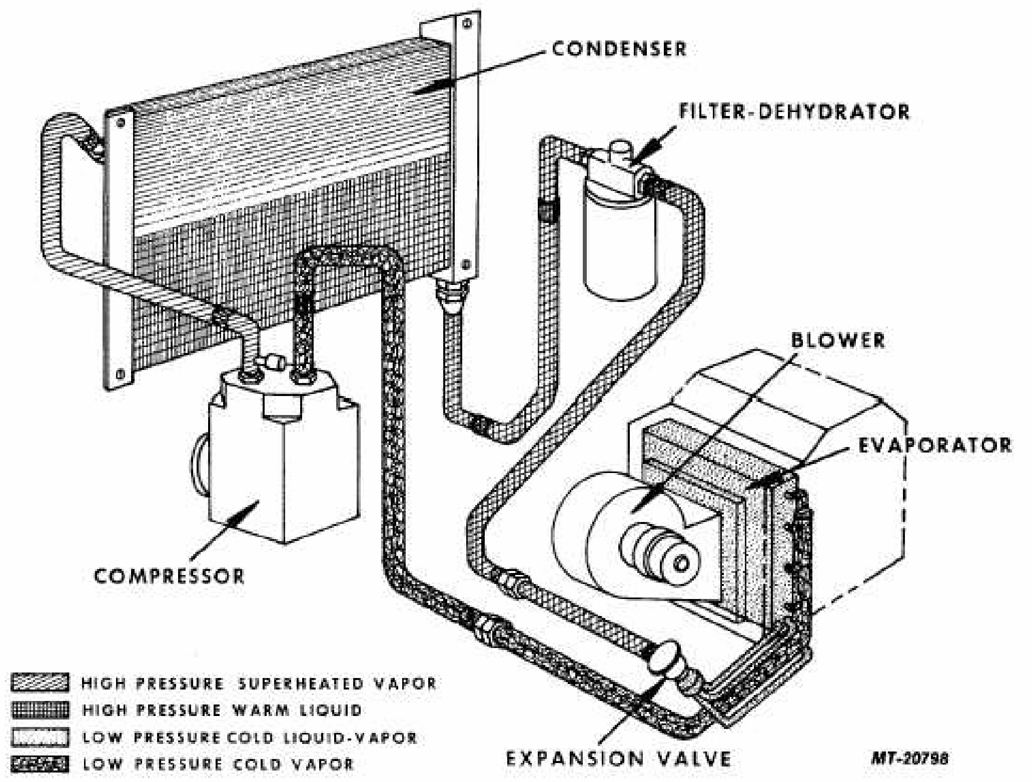
- **Gas cycle -** Air is most often this working fluid. The hot and cold gas-to-gas heat exchangers in are used. Less efficient than the vapor compression cycle because the gas cycle works on the reverse Brayton cycle instead of the reverse Rankine cycle
- **Thermoelectric refrigeration -** Thermoelectric cooling uses the Peltier effect to create a heat flux between the junction of two different types of materials. Commonly used in camping and portable coolers
- **Thermoacoustic refrigeration** uses sound waves in place of a compressor to create cooling power.

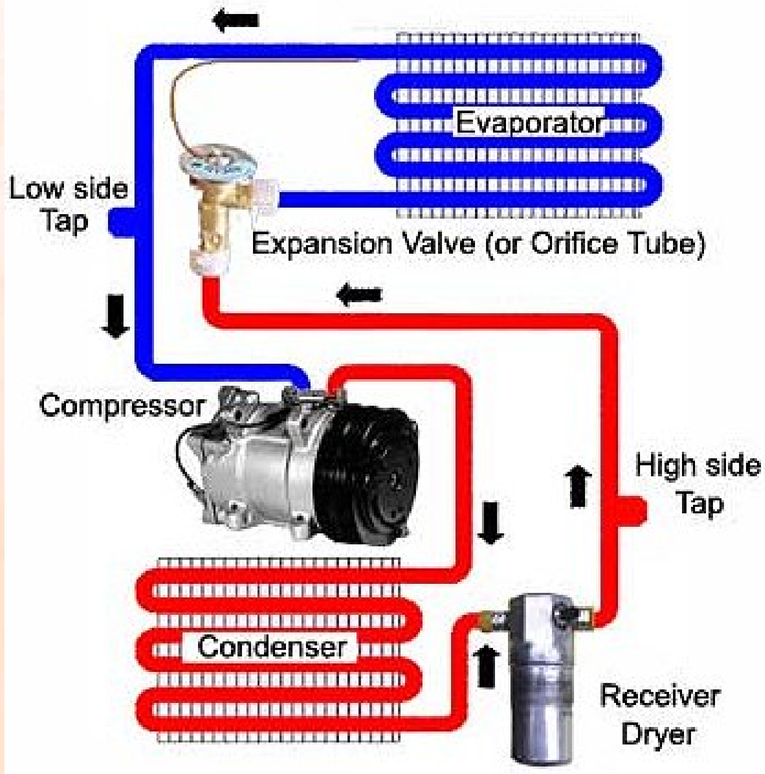
Application of VCRS

- Food Processing and storage - Refrigerator
- Building air conditioning system
- Car air conditioning system
- Water cooler
- Ice cube maker
- Low temperature drying process



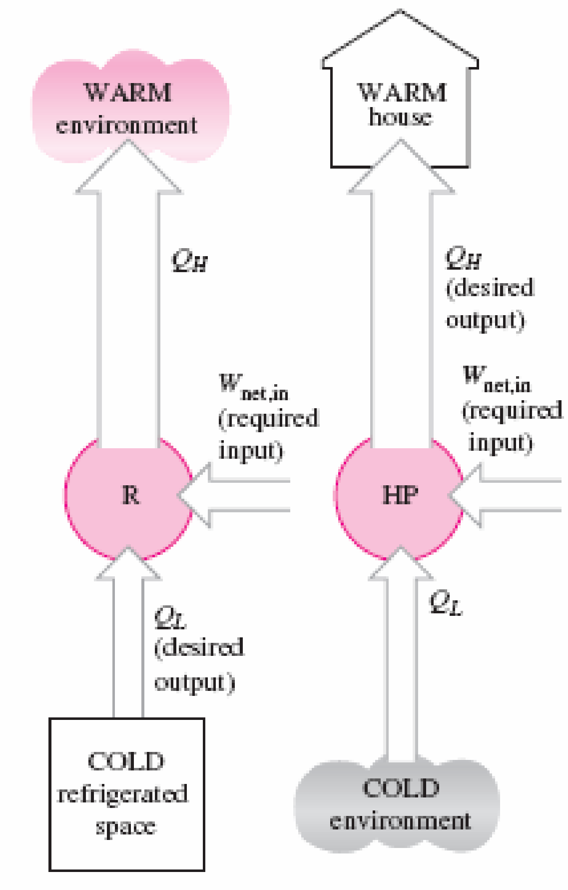
Operation of VCRS





REFRIGERATORS AND HEAT PUMPS

- The transfer of heat from a low-temperature to a high-temperature requires special devices called refrigerators or heat pumps.
- Refrigerators or heat pumps are cyclic devices and the working fluid used in the refrigeration cycles are called refrigerants.
- Refrigerators and heat pumps are essentially the same devices; they differ in their objectives only.
- The objective of a refrigerator is to maintain the refrigerated space at a low-temperature by removing heat (Q_L) from it.
- The objective of a heat pump is to maintain a heated space at a high- temperature by absorbing heat (Q_H) from environment.



(a) Refrigerator (b) Heat pump

REFRIGERATORS AND HEAT PUMPS

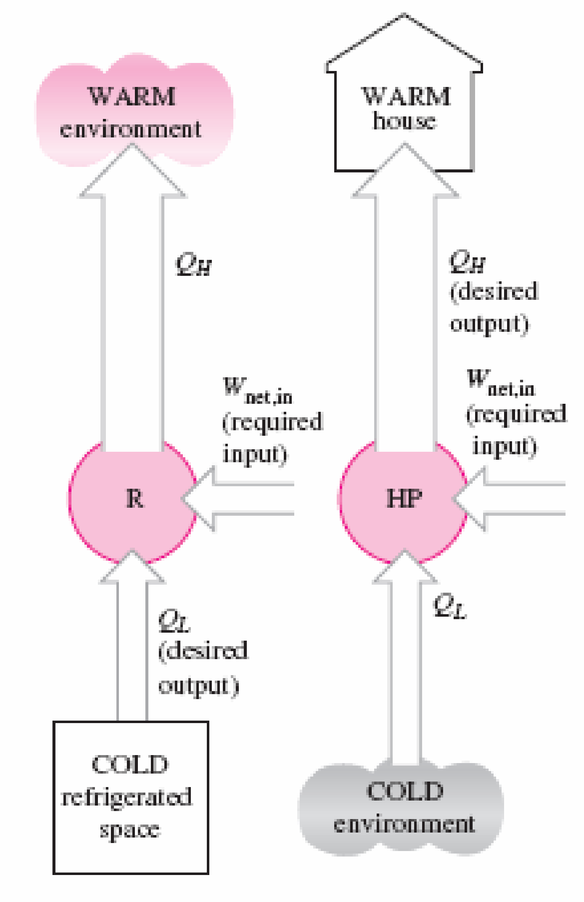
The performance of refrigerators and heat pumps is expressed in terms of the coefficient of performance (COP), defined as,

$$COP_R = \frac{Desired\ output}{Required\ input} = \frac{Cooling\ effect}{work\ input} = \frac{Q_L}{W_{net,in}}$$

$$COP_{HP} = \frac{Desired\ output}{Required\ input} = \frac{Heating\ effect}{work\ input} = \frac{Q_H}{W_{net,in}}$$

- Both COP_R and COP_{HP} can be greater than 1.
- For fixed values of Q_L and Q_H

$$COP_{HP} = COP_R + 1$$



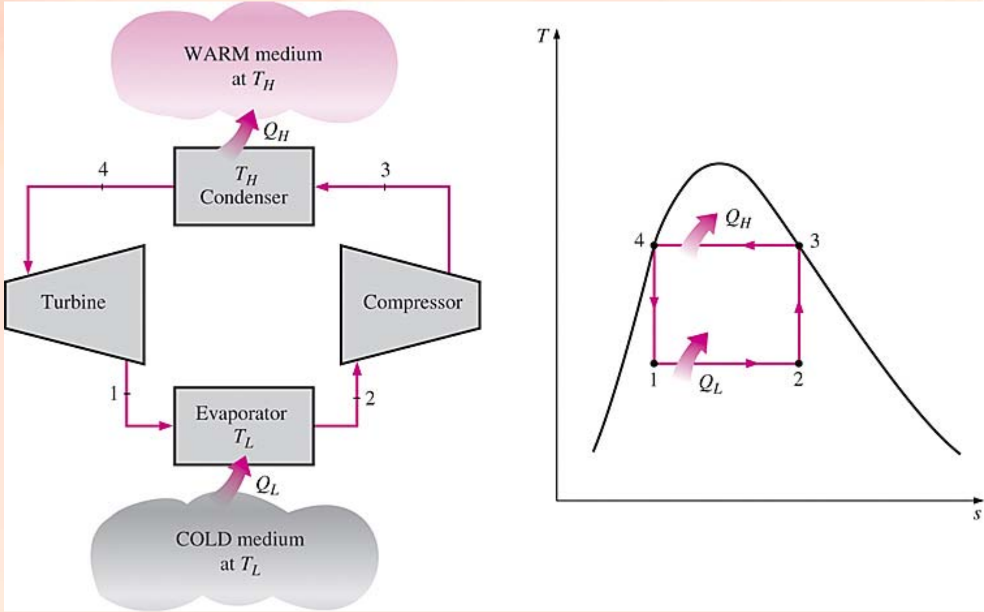
(a) Refrigerator (b) Heat pump

THE REVERSED CARNOT CYCLE

- The *most efficient* refrigeration cycle
- Not suitable model for refrigeration cycles because:
  - (i) process 2-3 involves compression of a liquid–vapor mixture - requires a compressor that will handle two phases,
  - (ii) process 4-1 involves expansion of high-moisture-content refrigerant in a turbine.

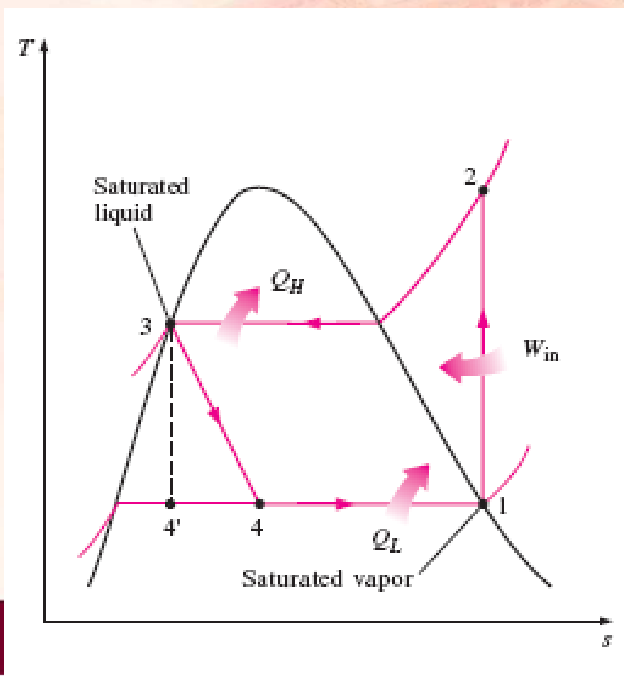
$$COP_{R,Carnot} = \frac{Q_L}{W_{net}} = \frac{T_L}{T_H - T_L} = \frac{1}{T_H/T_L - 1}$$

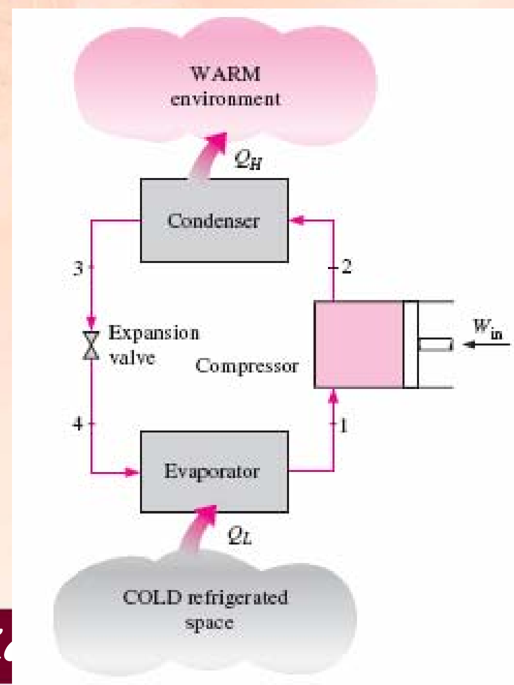
$$COP_{R,Carnot} = \frac{Q_H}{W_{net}} = \frac{T_H}{T_H - T_L} = \frac{1}{1 - T_L/T_H}$$

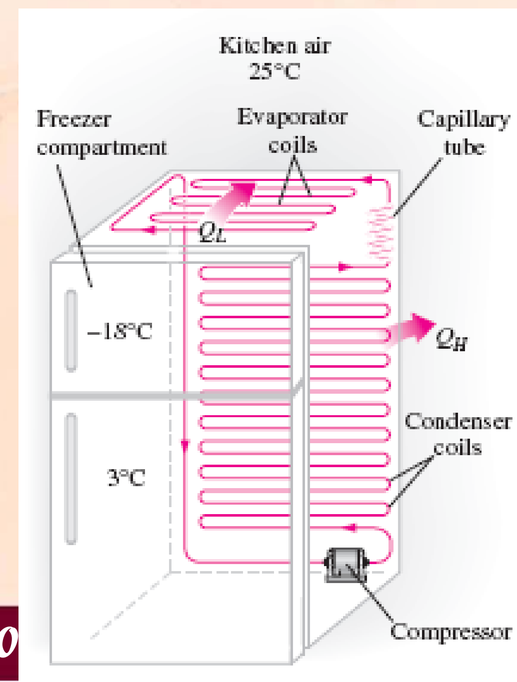


IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE

- The refrigerant is vaporized completely before it is compressed (process 4-1)
- The turbine is replaced with a throttling device (Process 3-4)
- Processes involved :
  - 1-2 : Isentropic compression in a compressor
  - 2-3 : Constant pressure heat rejection in a condenser
  - 3-4 : Throttling in an expansion device/valve
  - 4-1 : constant pressure heat absorption in an evaporator







IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE

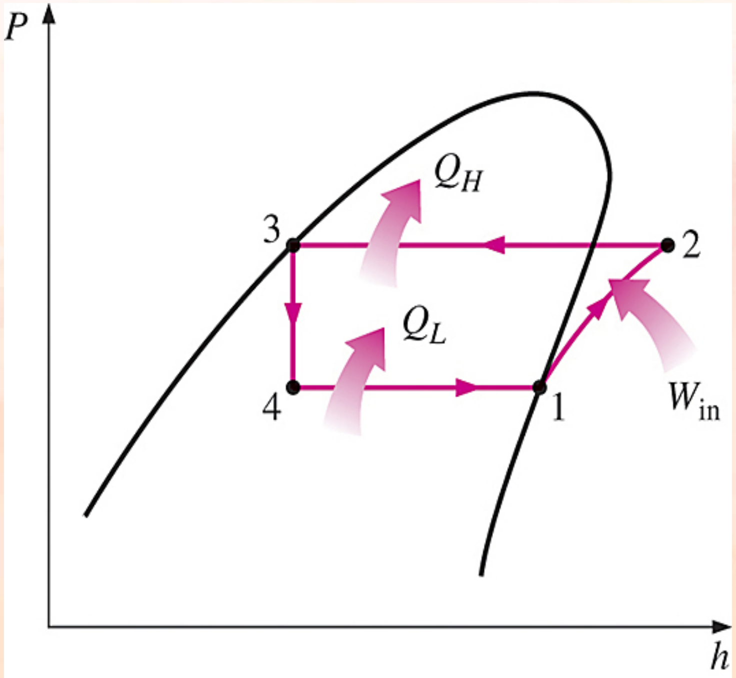
Analysis

$$COP_R = \frac{q_L}{w_{net}} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$COP_{HP} = \frac{q_H}{w_{net}} = \frac{h_2 - h_3}{h_2 - h_1}$$

where,

$$h_1 = h_{g\,@\,P_1} \text{ and } h_3 = h_{f\,@\,P_2}$$



The *P*-*h* diagram of an ideal vapor-compression refrigeration cycle.

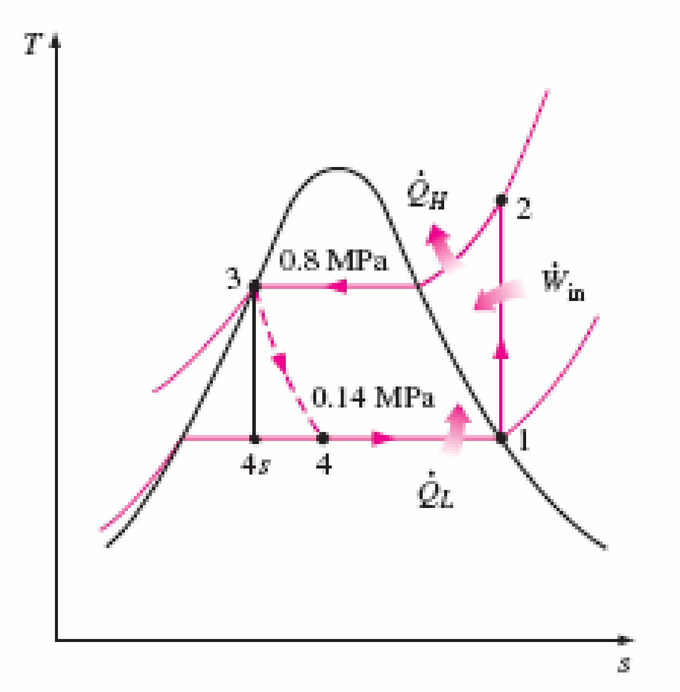
EXAMPLE 11-1

A refrigerator uses refrigerant 134a as the working fluid and operates on an ideal vapor compression refrigeration cycle between 0.14 and 0.8 MPa. If the mass flow rate of the refrigerant is 0.05 kg/s, determine (a) the rate of heat removal from the refrigerated space and the power input to the compressor (b) the rate of heat rejection to the environment (c) the COP of the refrigerator.

$h_1 = h_{g\ @\ 0.14\ MPa} = 239.16$ kJ/kg
$s_1 = h_{g\ @\ 0.14\ MPa} = 0.94456$ kJ/kgK

$P_2 = 0.8$ MPa
$s_2 = s_1$
} $h_2 = 275.39$ kJ/kg

$h_3 = h_{f\ @\ 0.8\ MPa} = 95.47$ kJ/kg
$h_4 = h_3 = 95.47$ kJ/kgK



EXAMPLE 11-1

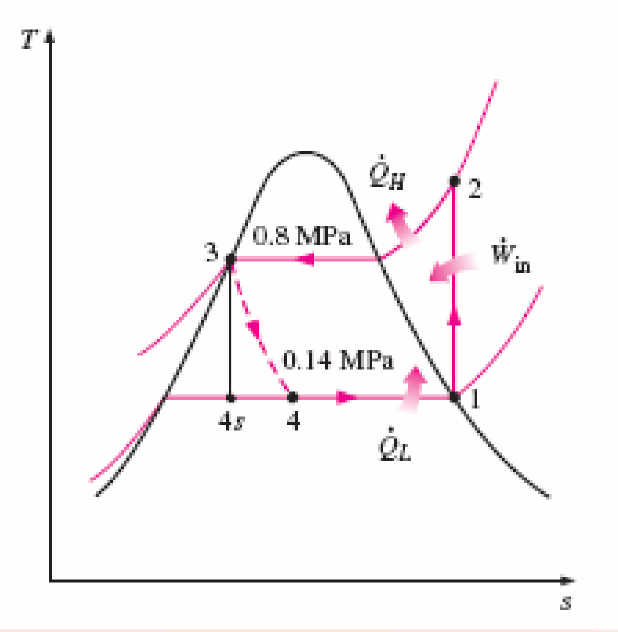
(a) $\dot{Q}_L = \dot{m}(h_1 - h_4) = 0.05(239.16 - 95.47) = 7.18\ kW$

$\dot{W}_{net} = \dot{m}(h_2 - h_1) = 0.05(275.39 - 239.16) = 1.81\ kW$

(b) $\dot{Q}_H = \dot{m}(h_2 - h_3) = 0.05(275.39 - 95.47) = 9.0\ kW$

or $\dot{Q}_H = \dot{Q}_L + \dot{W}_{net} = 7.18 + 1.81 = 8.99\ kW$

(c) $COP = \dfrac{\dot{Q}_L}{\dot{W}_{net}} = \dfrac{7.18}{1.81} = 3.97$



Problem 11-14

A refrigerator uses refrigerant-134a as the working fluid and operates on an ideal vapor-compression refrigeration cycle between 0.12 and 0.7 MPa. The mass flow rate of the refrigerant is 0.05 kg/s. Show the cycle on a T-s diagram with respect to saturation lines. Determine:

a) the rate of heat removal from the refrigerated space,

b) the power input to the compressor,

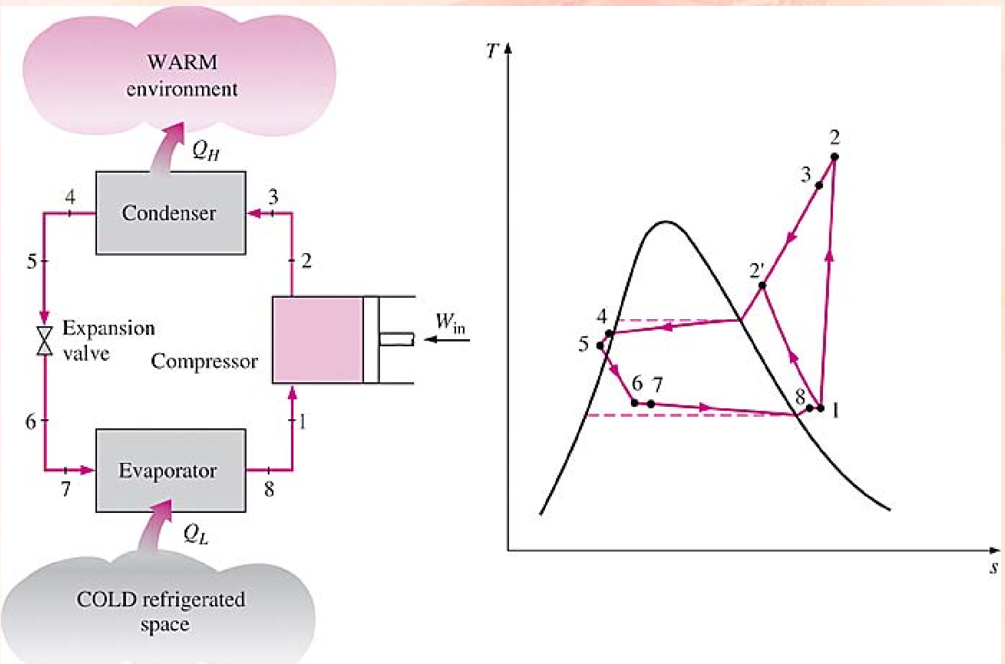
c) the rate of heat rejection to the environment, and

d) the coefficient of performance.

Answers: (a) 7.41 kW, 1.83 kW, (b) 9.23 kW, (c) 4.06

Actual Vapor-Compression Refrigeration Cycle

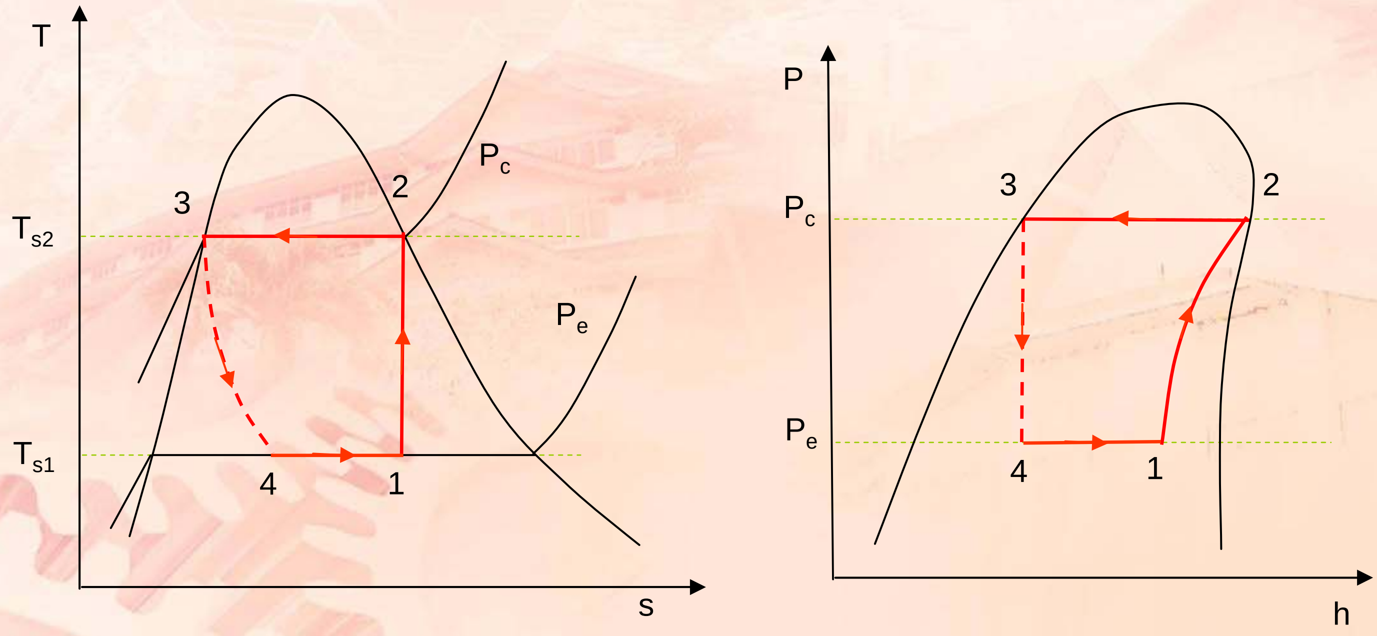
An actual vapor-compression refrigeration cycle involves irreversibilities in various components - mainly due to fluid friction (causes pressure drops) and heat transfer to or from the surroundings. As a result, the COP decreases.



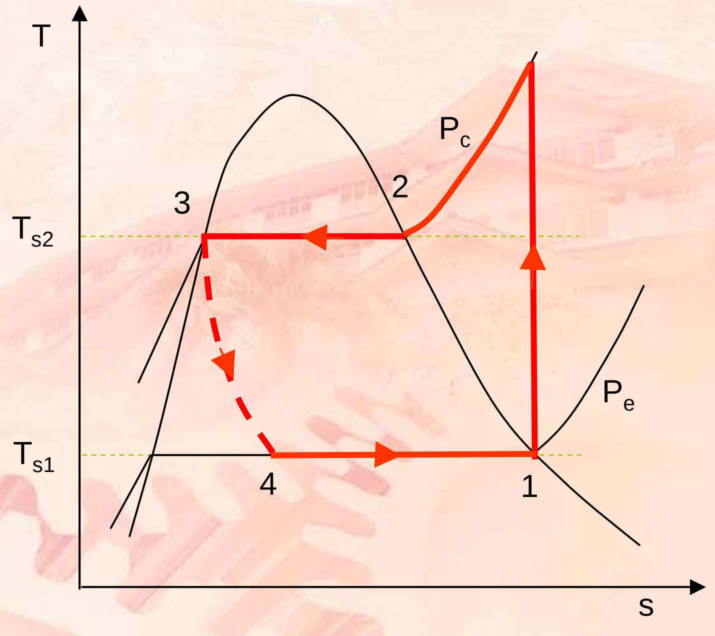
Differences

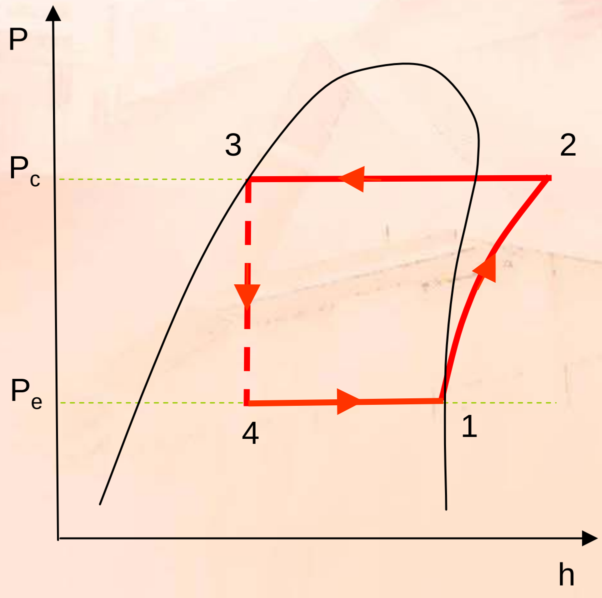
- Non-isentropic compression;
- Superheated vapor at evaporator exit;
- Sub-cooled liquid at condenser exit;
- Pressure drops in condenser and evaporator.

Actual Vapor-Compression Refrigeration Cycle

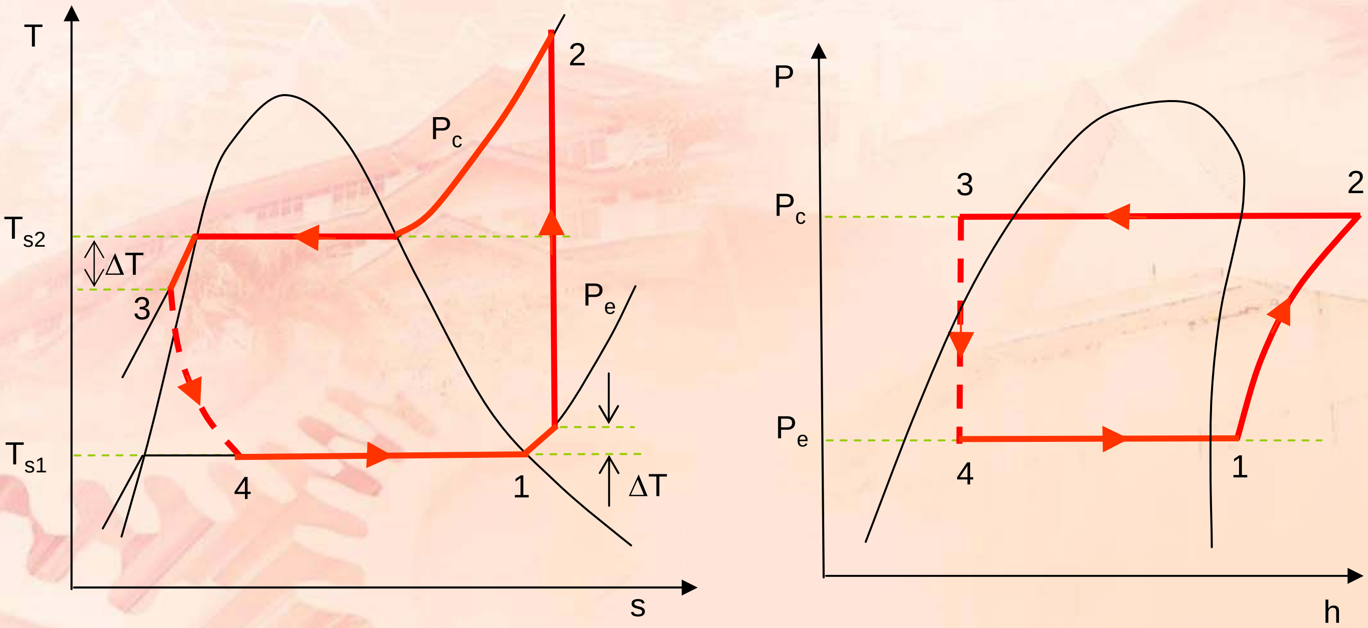


Actual Vapor-Compression Refrigeration Cycle

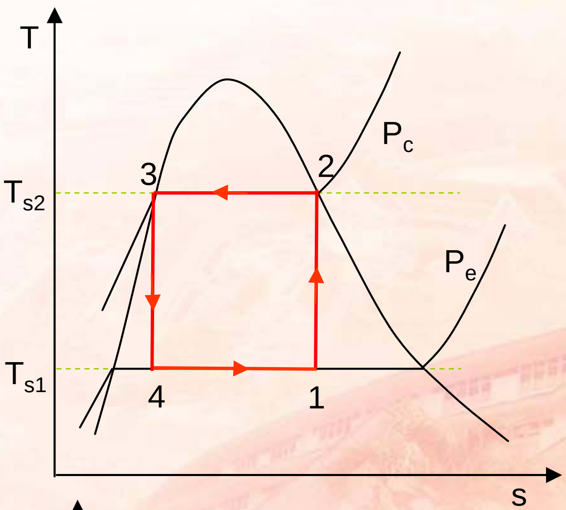


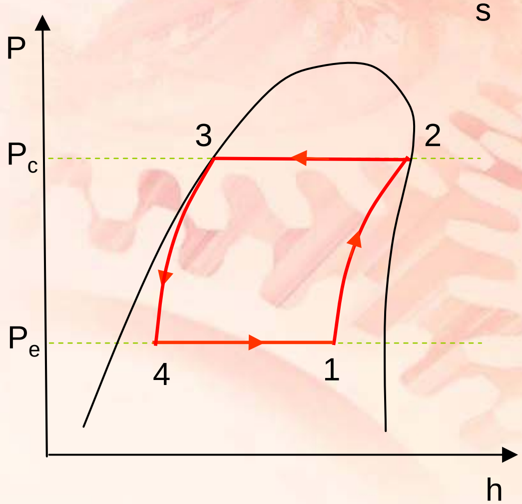


Actual Vapor-Compression Refrigeration Cycle



Actual Vapor-Compression Refrigeration Cycle





Reversed Carnot Cycle

Consider : P_c = 1.0 MPa, P_e = 0.14 MPa

State 2 : Saturated vapor, State 3 : Saturated liquid

$$h_2 = h_g = 270.99 \text{ kJ/kg}, \; s_2 = s_g = 0.91558 \text{ kJ/kgK}$$

$$x_1 = \frac{s_1 - s_f}{s_{fg}} = \frac{0.91558 - 0.11087}{0.83368} = 0.965$$

$$h_1 = 27.08 + 0.965(212.08) = 231.74 \text{ kJ/kg}$$

$$h_3 = h_f \text{ @ } 1000 \text{ kPa} = 107.32 \text{ kJ/kg}, \; s_3 = s_4 = s_f = 0.39189 \text{ kJ/kgK}$$

$$x_4 = \frac{0.39189 - 0.11087}{0.83368} = 0.337$$

$$h_4 = h_f + x_4 h_{fg} = 27.08 + 0.337(212.08) = 98.55 \text{ kJ/kg}$$

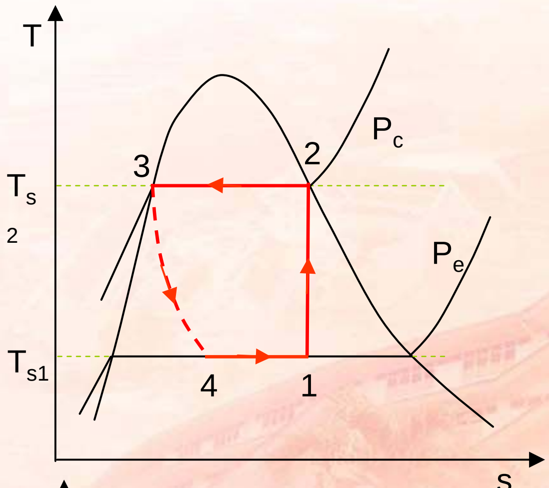
$$q_{41} = (h_1 - h_4) = 231.74 - 98.55 = 133.19 \text{ kJ/kg}$$

$$w_{net} = (h_2 - h_1) - (h_3 - h_4) = (270.99 - 231.74) - (107.32 - 98.55)$$
$$= 30.48 \text{ kJ/kg}$$

$$COP_R = \frac{q_{41}}{w_{12}} = \frac{133.19}{30.48} = 4.37 = \frac{(-18.77 + 273)}{(39.37 - (-18.77))} = 4.37$$

Actual Vapor-Compression Refrigeration Cycle

Consider : P_c = 1.0 MPa, P_e = 0.14 MPa
State 2 : Saturated vapor, State 3 : Saturated liquid



$$h_2 = h_g = 270.99 \text{ kJ/kg},\ s_2 = s_g = 0.91558 \text{ kJ/kgK} @ 1000 \text{ kPa}$$

$$x_1 = \frac{s_1 - s_f}{s_{fg}} = \frac{0.91558 - 0.11087}{0.83368} = 0.965$$

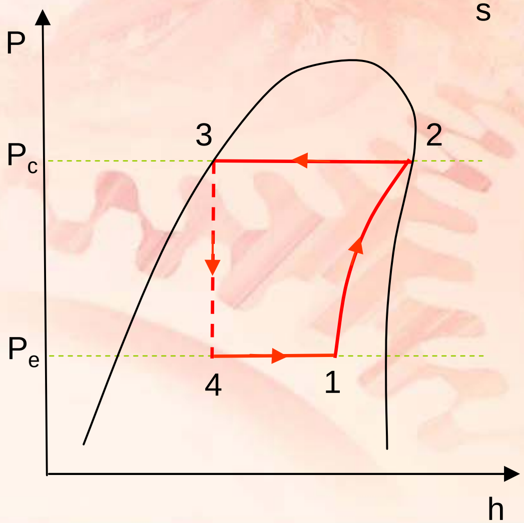
$$h_1 = 27.08 + 0.965(212.08) = 231.74 \text{ kJ/kg}$$

$$h_3 = h_4 = h_f @ 1000 \text{ kPa} = 107.32 \text{ kJ/KG}$$

$$q_{41} = (h_1 - h_4) = 231.74 - 107.32 = 124.42 \text{ kJ/kg} \downarrow$$

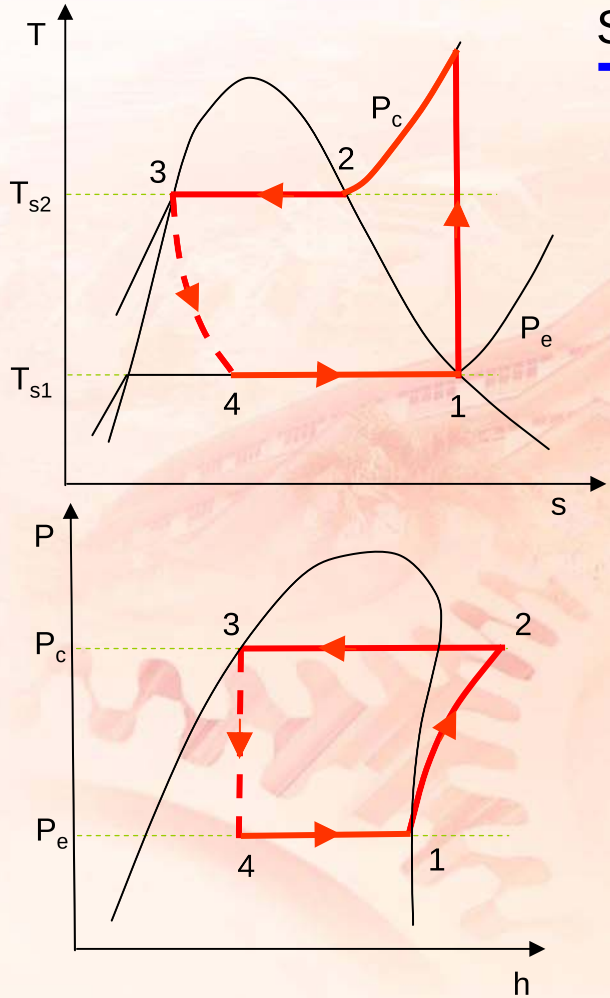
$$w_{12} = (h_2 - h_1) = 270.99 - 231.74 = 39.25 \text{ kJ/kg} \uparrow$$

$$COP_R = \frac{q_{41}}{w_{12}} = \frac{124.42}{39.25} = 3.17 \downarrow$$



Actual Vapor-Compression Refrigeration Cycle

Consider : P_c = 1.0 MPa, P_e = 0.14 MPa
State 1 : Saturated vapor, State 3 : Saturated liquid



$$h_1 = h_g = 239.16\ kJ/kg,\ s_1 = s_2 = s_g = 0.94456\ kJ/kgK$$

$$h_2 = \left(\frac{0.94456 - 0.9179}{0.9525 - 0.9179}\right)(282.74 - 271.71) + 271.71$$

$$= 280.21\ kJ/kg$$

$$h_3 = h_4 = h_f\ @\ 1000\ kPa = 107.32\ kJ/KG$$

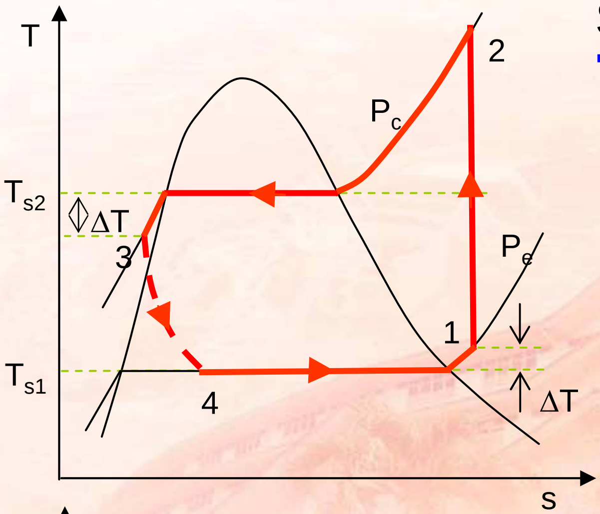
$$q_{41} = (h_1 - h_4) = 239.16 - 107.32 = 131.84\ kJ/kg \uparrow$$

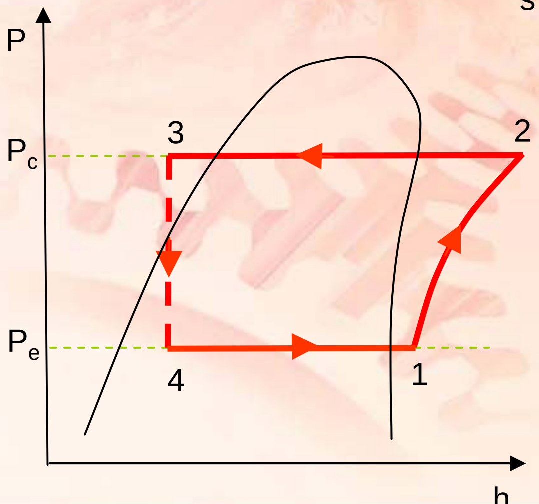
$$w_{12} = (h_2 - h_1) = 280.21 - 239.16 = 41.05\ kJ/kg \uparrow$$

$$COP_R = \frac{q_{41}}{w_{12}} = \frac{131.84}{41.05} = 3.21 \uparrow$$

Actual Vapor-Compression Refrigeration Cycle

Consider : P_c = 1.0 MPa, P_e = 0.14 MPa
State 1 : T_1 = -10°C, State 3 : T_3 = 34°C





$$h_1 = 246.36 \text{ kJ/kg}, s_1 = s_2 = 0.9724 \text{ kJ/kgK}$$

$$h_2 = \left(\frac{0.9724 - 0.9525}{0.9850 - 0.9525}\right)(293.38 - 282.74) + 282.74$$

$$= 289.25 \text{ kJ/kg}$$

$$h_3 = h_4 = h_f \ @ \ 34^oC = 99.40 \text{ kJ/KG}$$

$$q_{41} = (h_1 - h_4) = 246.36 - 99.40 = 146.96 \text{ kJ/kg} \uparrow$$

$$w_{12} = (h_2 - h_1) = 289.25 - 246.36 = 42.89 \text{ kJ/kg} \uparrow$$

$$COP_R = \frac{q_{41}}{w_{12}} = \frac{146.96}{42.89} = 3.43 \uparrow$$

EXAMPLE 11-2

Refrigerant 134a enters the compressor of a refrigerator as superheated vapor at 0.14 MPa and -10ºC at a rate of 0.05 kg/s and leaves at 0.8 MPa and 50ºC. The refrigerant is cooled in the condenser to 26ºC and 0.72 MPa and is throttled to 0.15 MPa. Disregarding any heat transfer and pressure drops in the connecting lines between the components, determine (a) the rate of heat removal from the refrigerated space and the power input to the compressor (b) the isentropic efficiency of the compressor and (c) the COP of the refrigerator.

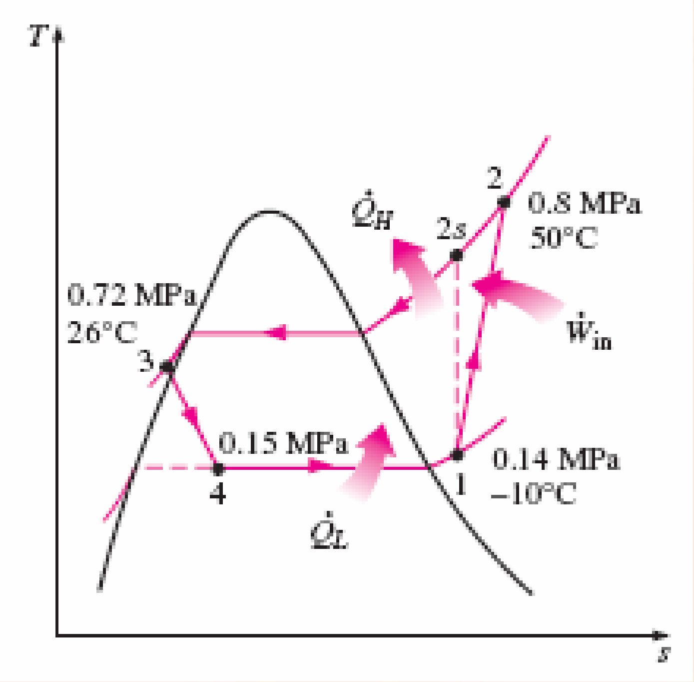
$P_1 = 0.14$ MPa, $T_1 = -10^oC$ } $h_1 = 246.36$ kJ/kg

$P_2 = 0.8$ MPa, $T_2 = 50^oC$ } $h_2 = 286.69$ kJ/kg

$P_3 = 0.72$ MPa, $T_3 = 26^oC$ } $h_3 \cong h_f$ @ $26^oC = 87.83$ kJ/kg

$P_{2s} = 0.8$ MPa, $s_{2s} = s_1 = 0.9724$ kJ/kgK } $h_{2s} = 284.21$ kJ/kg

$h_4 \cong h_3 = 87.83$ kJ/kgK



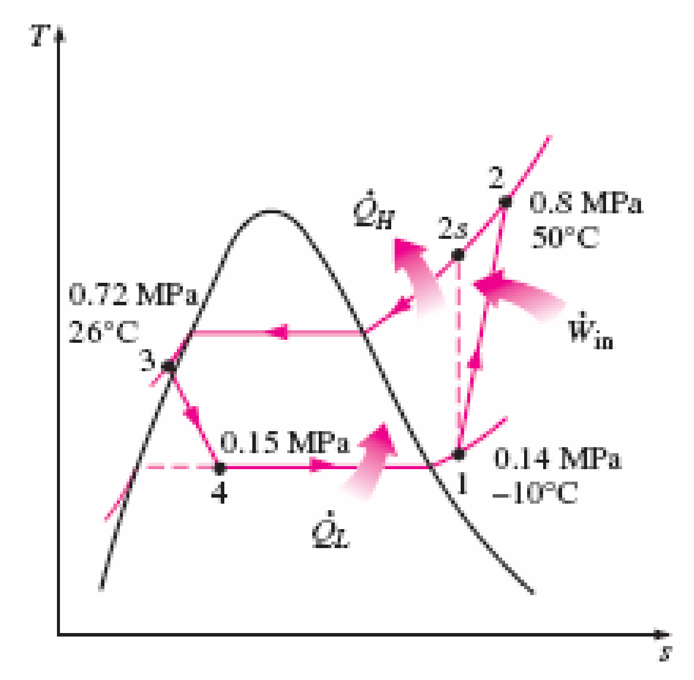
EXAMPLE 11-2

(a) $\dot{Q}_L = \dot{m}(h_1 - h_4) = 0.05(246.36 - 87.83) = 7.93\ kW$

$\dot{W}_{net} = \dot{m}(h_2 - h_1) = 0.05(286.69 - 246.36) = 2.02\ kW$

(b) $$\eta_c = \frac{h_{2s} - h_1}{h_2 - h_1} = \frac{284.21 - 246.36}{286.69 - 246.36} = 0.939 \text{ or } 93.9\%$$

(c) $$COP = \frac{\dot{Q}_L}{\dot{W}_{net}} = \frac{7.93}{2.02} = 3.93$$



Problem 11–17

Refrigerant-134a enters the compressor of a refrigerator as superheated vapor at 0.14 MPa and -10°C at a rate of 0.12 kg/s, and it leaves at 0.7 MPa and 50°C. The refrigerant is cooled in the condenser to 24°C and 0.65 MPa, and it is throttled to 0.15 MPa. Disregarding any heat transfer and pressure drops in the connecting lines between the components, show the cycle on a T-s diagram with respect to saturation lines, and determine:

a) the rate of heat removal from the refrigerated space,
b) the power input to the compressor,
c) the isentropic efficiency of the compressor, and
d) the COP of the refrigerator.

Answers: (a) 19.4 kW, 5.06 kW, (b) 82.5 percent, (c) 3.83

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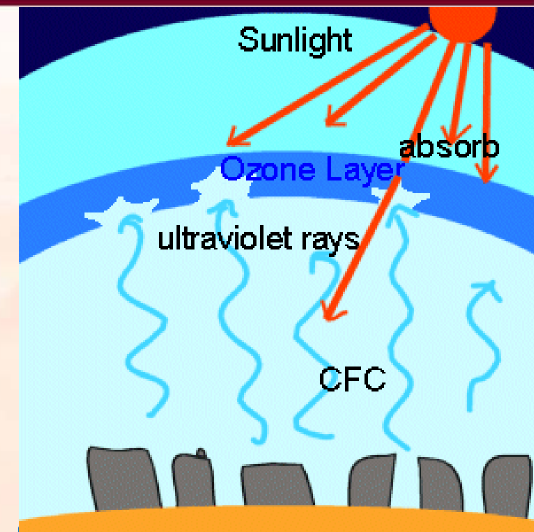
Selecting the Right Refrigerant

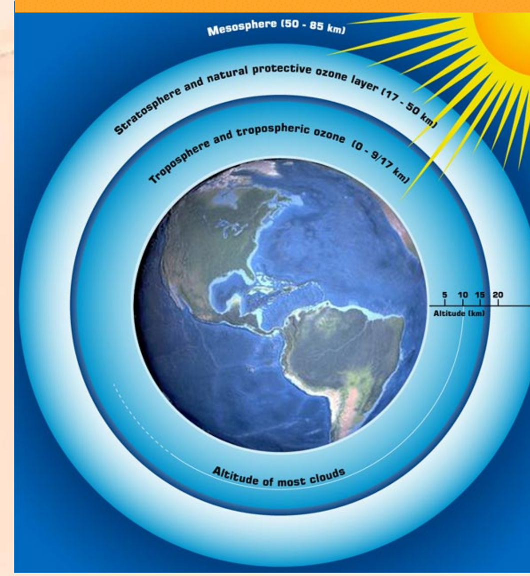
- Refrigerants may be used in refrigeration systems such as chlorofluorocarbons (CFCs), ammonia, hydrocarbons (propane, ethane, ethylene, etc.), carbon dioxide, air and even water (in applications above the freezing point).
- Before concerns about depletion of the ozone layer arose in the 1980s, the most widely used refrigerants were the R-12 (CFC) and R-22 (HCFC).
- R-12 being more common in automotive air conditioning and small refrigerators, and R-22 being used for residential and light commercial air conditioning, refrigerators, and freezers
- CFCs allow more ultraviolet radiation into the earth's atmosphere by destroying the protective ozone layer and thus contributing to the greenhouse effect that causes global warming. Refrigerants that are friendly to the ozone layer have been developed.
- The Montreal Protocol, 1987 and the Copenhagen Agreement, 1992 mandate a stop to all production of Chlorinated Fluorocarbon (CFC) in 1996. Example of CFC : R11, R12, R21 and R502.

Selecting the Right Refrigerant

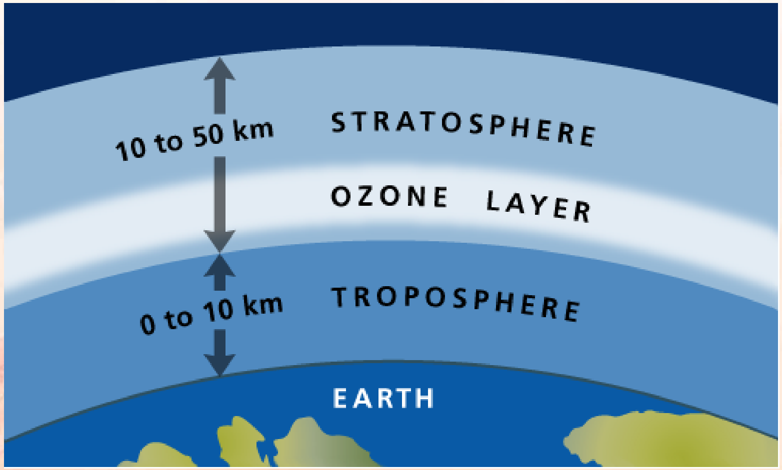
Ozon Layer

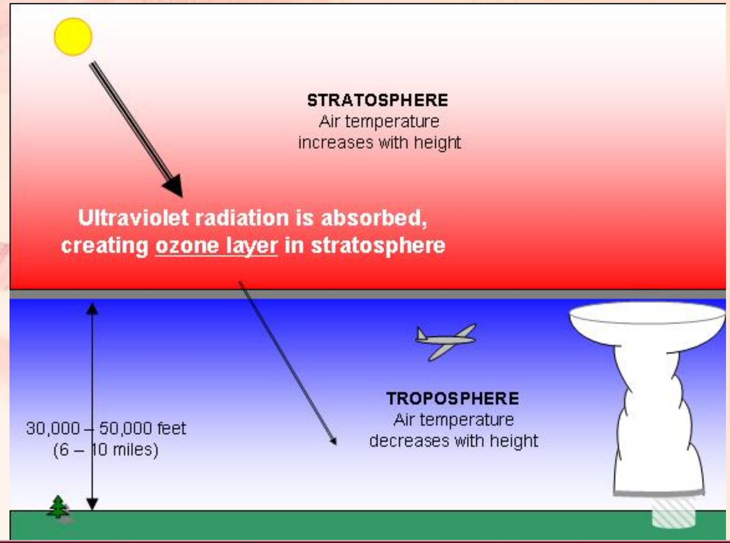
- The ozone layer is a deep layer in the stratosphere, encircling the Earth, containing relatively high concentrations of ozone (O_3)
- This layer shields the entire earth from the harmful ultraviolet radiation that comes from the sun that cause skin cancer and other health problems.
- The ozone layer can be depleted by free radical catalysts, including nitric oxide (NO), nitrous oxide (N_2O), hydroxyl (OH), atomic chlorine (Cl), and atomic bromine (Br)





Ozon Layer


10 to 50 km
STRATOSPHERE
OZONE LAYER
0 to 10 km
TROPOSPHERE
EARTH


STRATOSPHERE
Air temperature increases with height
Ultraviolet radiation is absorbed, creating ozone layer in stratosphere
TROPOSPHERE
Air temperature decreases with height
30,000 – 50,000 feet (6 – 10 miles)

Selecting the Right Refrigerant

- Hydrochloro Fluorocarbon (HCFC) and Hydro Fluorocarbon (HFC) as alternative refrigerants
  - Example of HCFCs : R22, R123 and R124
  - Example of HFC : R134a
- HCFCs have 2 to 10% ozone deflecting potential and have atmospheric lifetime 2 to 25 years compare to more than 100 years for CFCs
- R-134a and certain blends are now replacing chlorinated compounds (CFCs).
- 50/50 blend of R-32 and R-125 now being increasingly substituted for R-22 is R-410A, marketed under the trade name Puron
- Blend of R-32, R-125, and R-134a with a higher critical temperature, and lower GWP than R-410A is R-407C.
- The use of HCFCs and HFCs results in slightly lower efficiencies as compared to CFCs
- Two important parameters to be considered - the temperatures of the refrigerated space and the environment with which the refrigerant exchanges heat.

Selecting the Right Refrigerant

TABLE 4.1 PROPERTIES OF COMMONLY USED REFRIGERANTS

Refrigerant	Boiling Point ** (°C)	Freezing Point (°C)	Vapor Pressure * (kPa)	Vapor Volume * (m3 / kg)	Enthalpy * Liquid (kJ / kg)	Enthalpy * Vapor (kJ / kg)
R - 11	-23.82	-111.0	25.73	0.61170	191.40	385.43
R - 12	-29.79	-158.0	219.28	0.07702	190.72	347.96
R - 22	-40.76	-160.0	354.74	0.06513	188.55	400.83
R - 502	-45.40	---	414.30	0.04234	188.87	342.31
R - 7 (Ammonia)	-33.30	-77.7	289.93	0.41949	808.71	487.76

* *At -10°C*

** *At Standard Atmospheric Pressure (101.325 kPa)*

Selecting the Right Refrigerant

TABLE 4.2 PERFORMANCE OF COMMONLY USED REFRIGERANTS*

Refrigerant	Evaporating Press (kPa)	Condensing Press (kPa)	Pressure Ratio	Vapor Enthalpy (kJ / kg)	COP^{**}_{carnot}
R - 11	20.4	125.5	6.15	155.4	5.03
R - 12	182.7	744.6	4.08	116.3	4.70
R - 22	295.8	1192.1	4.03	162.8	4.66
R - 502	349.6	1308.6	3.74	106.2	4.37
R - 717	236.5	1166.5	4.93	103.4	4.78

* *At -15°C Evaporator Temperature, and 30°C Condenser Temperature*

** *COP_{carnot} = Coefficient of Performance = $Temp._{Evap.}$ / ($Temp._{Cond.}$ -$Temp_{Evap.}$)*

Selecting the Right Refrigerant

TABLE 4.3 COMPARISON OF DIFFERENT TYPES OF REFRIGERATION PLANTS

(Source : Ashrae & Vendor Information)

S. No	Parameters	Vapour Compression Chillers			Vapour Absorption Chiller				
					LiBr				Ammonia
		Reciprocating	Centrifugal	Screw	Single Effect	Double Effect	Half Effect	Triple Effect	Single Stage
1	Refrigeration Temp. Range (Brine / Water)	+7 to -30°C	+7 to -0°C	+7 to -25°C	Above 6°C				Upto –33°C
2	Energy Input	Electricity	Electricity	Electricity	Heat (Steam / Hot Water / Hot Oil/Direct Fired)	Heat (Steam / Hot Water / Hot Oil/ Direct Fired)	Heat (Hot Water)	Heat (Steam /Hot Oil /Direct Fired)	Heat (Steam/ Hot Water / Hot Oil)
3	Heat Input Temp. Range -Maximum -Minimum	-	-	-	Minimum 85°C	Minimum 130°C	Minimum 55°C	Minimum 190°C	Minimum 85°C
4	Typical Energy to TR Ratio								
	Air Conditioning Temp. Range	0.7-0.9 kW/TR	0.63kW/TR	0.65 kW/TR	5000 kcal/TR	2575 kcal/TR	7500 kcal/TR	2000 kcal/TR	4615 kcal/TR
	Subzero Temp. Range	1.25 to 2.5 kW/TR	——	1.25 to 2.5 kW/TR	–––	——	——	-----	6666 kcal/hr
5	Refrigerant	R11,R123,R134a Ammonia	R22, R12	R22, R134a Ammonia	Pure Water	Pure Water	Pure Water	Pure Water	Pure Ammonia
6	Absorbent	–––	–––	–––	Water-LiBr solution	Water-LiBr solution	Water-LiBr solution	Water-LiBr solution	Ammonia-LiBr solution
7	Typical single unit capacity range								
	Air Condition temp. range	1-150 TR	300 TR & above	50-200 TR	30 TR & above	30 TR & above	30 TR & above	50 TR & above	30 TR & above
	Subzero temp. range	10-50 TR	–––	50-200 TR	–––	–––	–––	–––	30 TR & above
8	Typical COP at Part Load upto 50%	Reduces at part load	Reduces at part load	Improves by 15-20%	Marginal Improvement at Part Load				No variation
9	Typical Internal Pressure Levels -Low -High Typical Internal Temp. Levels	0.15-0.40 bar a 1.20-1.50 bar a -25 to 50°C	2.5-3.5 bar a 11-12 bar -5 to 50°C	2-5.5 bar 18-20 bar -25 to 50°C	5-6 mm Hg (abs) 60-70 mm Hg (abs) +4 to 75°C	5-6 mm Hg (abs) 370-390 mm Hg (abs) +4 to +130°C	5-6 mm Hg (abs) 60-70 mm Hg (abs) +4 to 130°C	5-6 mm Hg (abs) 2 kg/cm^2 (a) +4 to 160°C	1.2kg/cm^2(a) 18 kg/cm2(a) -25 to +150°C

Innovative Vapor-compression Refrigeration Systems

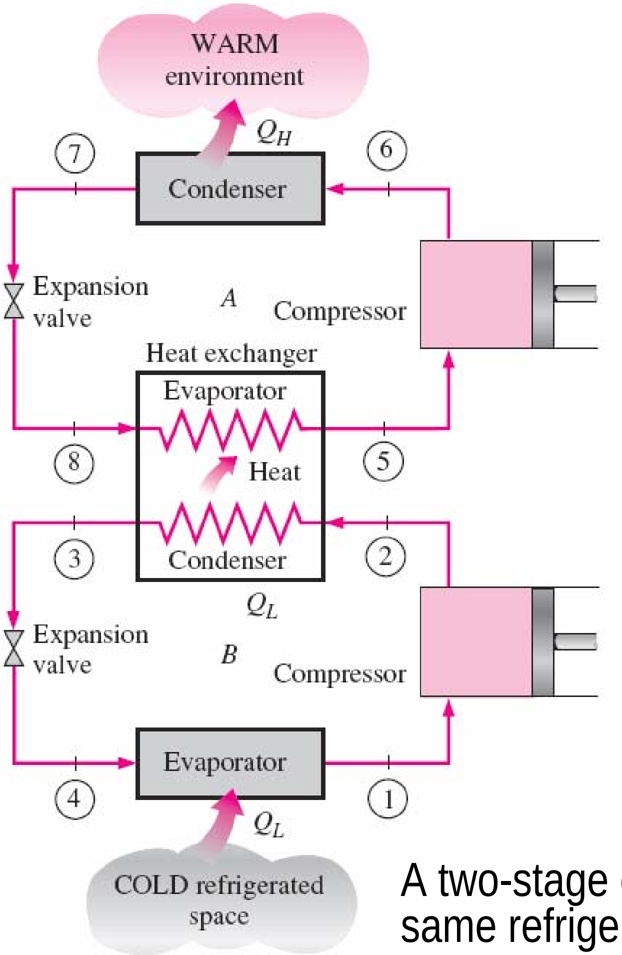
- The simple vapor-compression refrigeration cycle is the most widely used refrigeration cycle, and is adequate for most refrigeration applications.
- The ordinary vapor-compression refrigeration systems are simple, inexpensive, reliable, and practically maintenance-free.
- However, for large industrial applications, *efficiency* (not simplicity) is the major concern.
- For moderately very low temperature applications, some innovative refrigeration systems are used. The following cycles will be discussed:
    - Cascade refrigeration systems
    - Multistage compression refrigeration systems
    - Multipurpose refrigeration systems with a single compressor
    - Liquefaction of gases

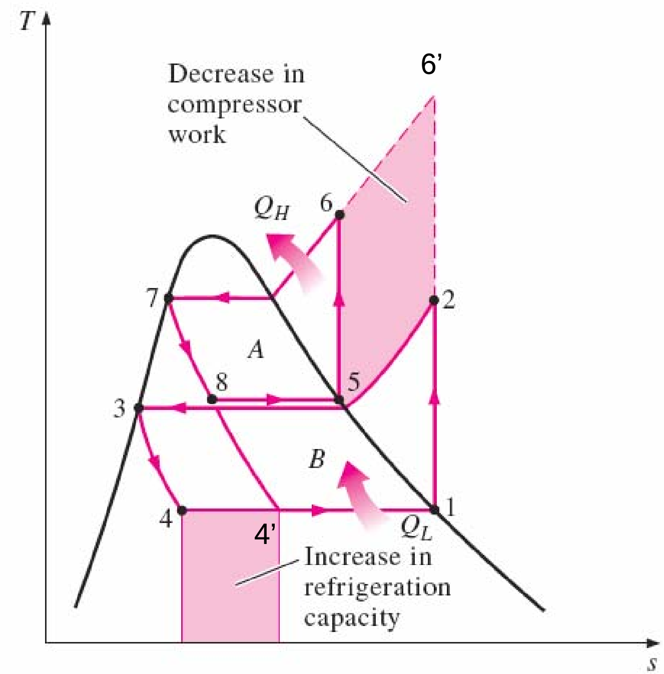
Cascade Refrigeration Systems

- Some industrial applications require moderately low temperatures, and the temperature range they involve may be too large for a single vapor compression refrigeration cycle to be practical.
- A large temperature range also means a large pressure range in the cycle and a poor performance for a reciprocating compressor.
- One way of dealing with such situations is to perform the refrigeration process in stages, that is, to have two or more refrigeration cycles that operate in series.
- Such refrigeration cycles are called cascade refrigeration cycles.

Cascade Refrigeration Systems

A two-stage cascade refrigeration cycle is shown. The two cycles are connected through the heat exchanger in the middle, which serves as the evaporator for the topping cycle and the condenser for the bottoming cycle.





A two-stage cascade refrigeration system with the same refrigerant in both stages.

Cascade Refrigeration Systems

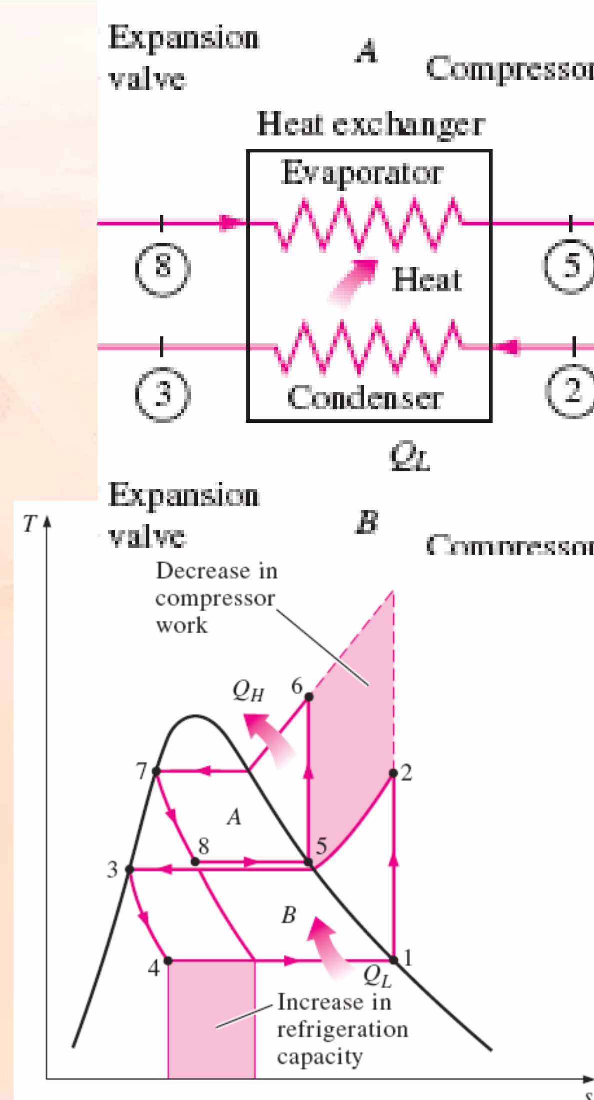
Analysis

- Assuming the heat exchanger is well insulated and the kinetic and potential energies are negligible, the heat transfer from the fluid in the bottoming cycle should be equal to the heat transfer to the fluid in the topping cycle.
- Thus, the ratio of mass flow rates through each cycle should be

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

- The coefficient of performance of the cascade system is

$$COP_{R,cascade} = \frac{\dot{Q}_L}{\dot{W}_{net,in}} = \frac{\dot{m}_B(h_1 - h_4)}{\dot{m}_A(h_6 - h_5) + \dot{m}_B(h_2 - h_1)}$$



EXAMPLE 11-3

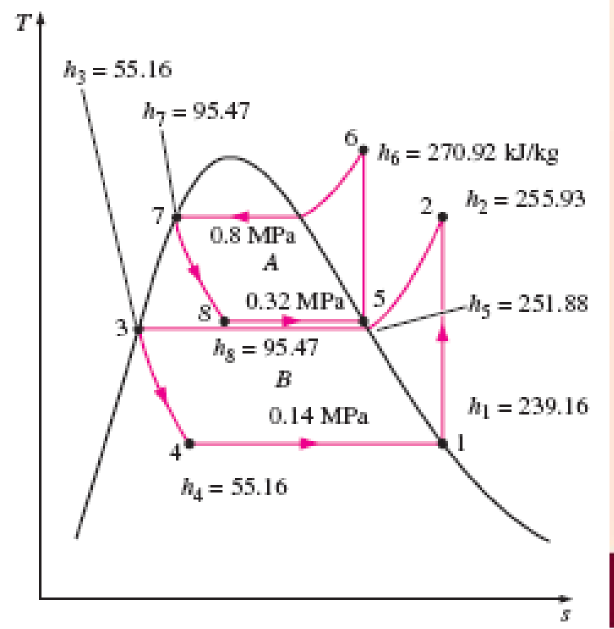
Consider a two-stage cascade refrigeration system operating between the pressure limits of 0.8 and 0.14 MPa. Each stage operates on an ideal vapor compression refrigeration cycle with refrigerant-134a as the working fluid. Heat rejection from the lower cycle to the upper cycle takes place in an adiabatic counter flow heat exchanger where both streams enter at about 0.32 MPa. (In practice, the working fluid of the lower cycle is at a higher pressure and temperature in the heat exchanger for effective heat transfer). If the mass flow rate of the refrigerant through the upper cycle is 0.05 kg/s, determine (a) the mass flow rate of the refrigerant through the lower cycle (b) the rate of heat removal from the refrigerated space and the power input to the compressor and (c) the COP of the refrigeration system.

(a) $\dot{E}_{out} = \dot{E}_{in} \rightarrow \dot{m}_A h_5 + \dot{m}_B h_3 = \dot{m}_A h_8 + \dot{m}_B h_2$

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

$$(0.05)(251.88 - 95.47) = \dot{m}_B(255.93 - 55.16)$$

$$\dot{m}_B = 0.0390 \text{ kg/s}$$



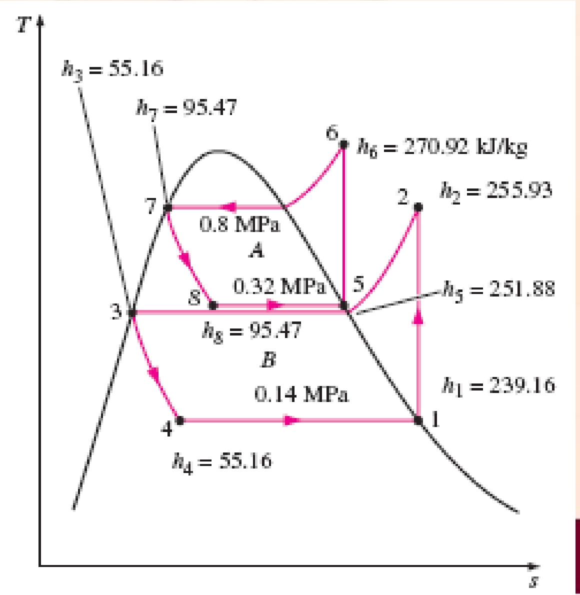
EXAMPLE 11-3

(b) The rate of heat removal by a cascade cycle is the rate of absorbtion in the evaporator of the lowest stage.

$$\dot{Q}_L = \dot{m}_B(h_1 - h_4) = 0.0390(239.16 - 55.16) = 7.18 \text{ kW}$$

$$\begin{aligned}\dot{W}_{in} &= \dot{W}_{comp\ 1} + \dot{W}_{comp\ 11} \\ &= \dot{m}_A(h_6 - h_5) + \dot{m}_B(h_2 - h_1) \\ &= (0.05)(270.92 - 251.88) + (0.0390)(255.93 - 239.16) \\ &= 1.61 \text{ kW}\end{aligned}$$

(c) $$COP_R = \frac{\dot{Q}_L}{\dot{W}_{net,in}} \frac{7.18}{1.61} = 4.46$$



Problem 2

Consider a two-stage cascade refrigeration system operating between pressure limits of 0.8 and 0.14 MPa. Each stage operates on the ideal vapor-compression refrigeration cycle with refrigerant-134a as the working fluid. Heat rejection from the lower cycle to the upper cycle takes place in an adiabatic counter-flow heat exchanger where both streams enter at about 0.4 MPa. If the mass flow rate of the refrigerant through the upper cycle is 0.24 kg/s, determine the:

a) mass flow rate of the refrigerant through the lower cycle,
b) rate of heat removal from the refrigerated space,
c) power input to the compressor, and
d) coefficient of performance of this cascade refrigerator.

Answers: (a) 0.195 kg/s, (b) 34.2 kW, 7.63 kW, (c) 4.49

Problem 11–47

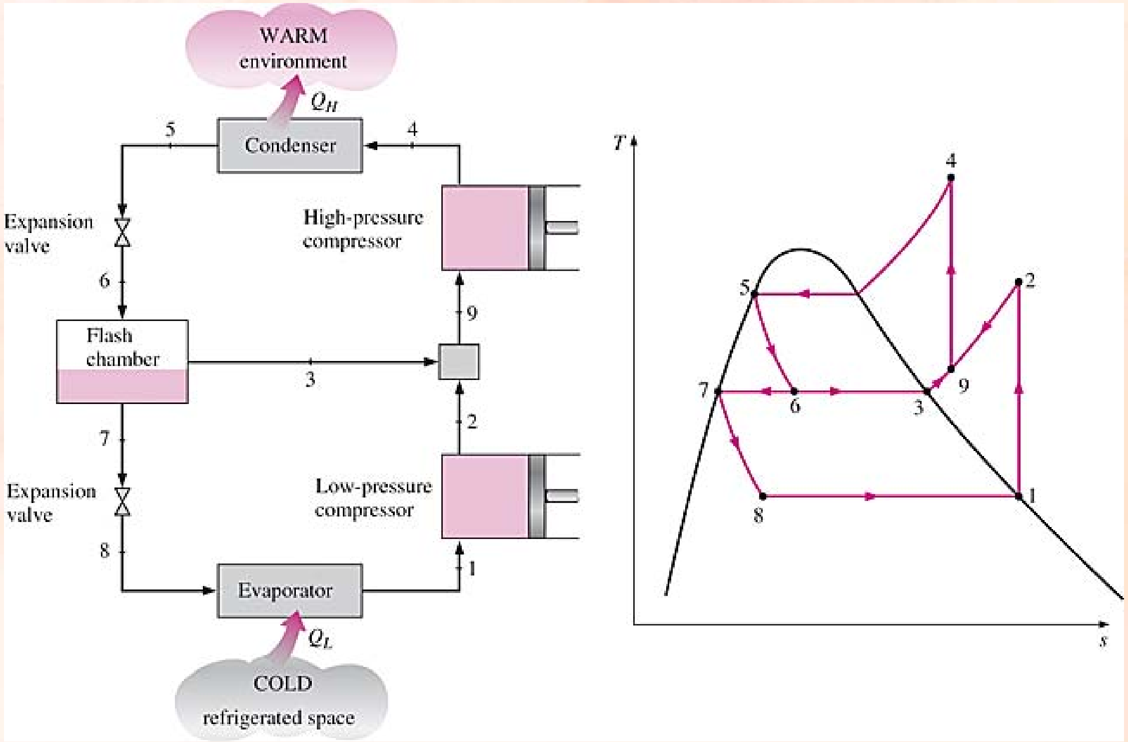
Consider a two-stage cascade refrigeration system operating between pressure limits of 1.2 MPa and 200 kPa with refrigerant-134a as the working fluid. Heat rejection from the lower cycle to the upper cycle takes place in an adiabatic counter-flow heat exchanger where the pressure in the upper and lower cycles are 0.4 and 0.5 MPa, respectively. In both cycles, the refrigerant is a saturated liquid at the condenser exit and a saturated vapor at the compressor inlet, and the isentropic efficiency of the compressor is 80 percent. If the mass flow rate of the refrigerant through the lower cycle is 0.15 kg/s, determine the:

a) mass flow rate of the refrigerant through the upper cycle,
b) rate of heat removal from the refrigerated space, and
c) coefficient of performance of the system.

Answers: (a) 0.212 kg/s, (b) 25.7 kW, (c) 2.68

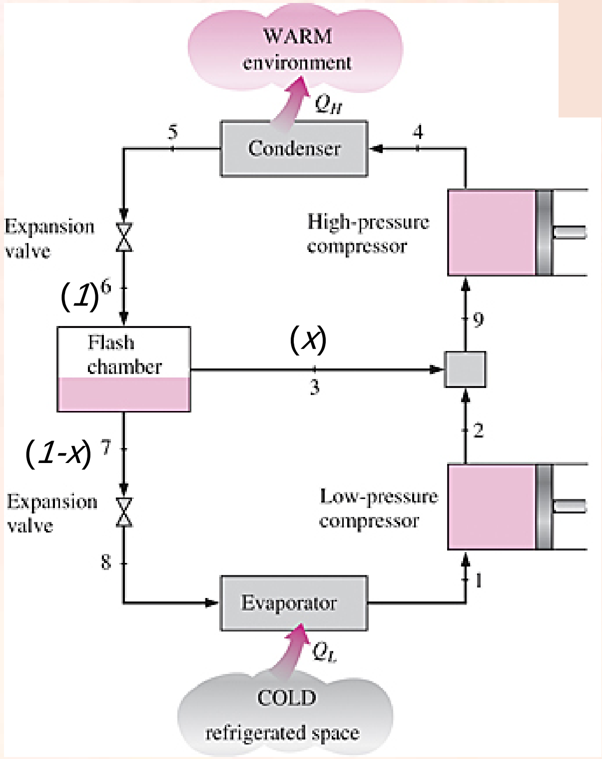
Multistage Compression Refrigeration Systems

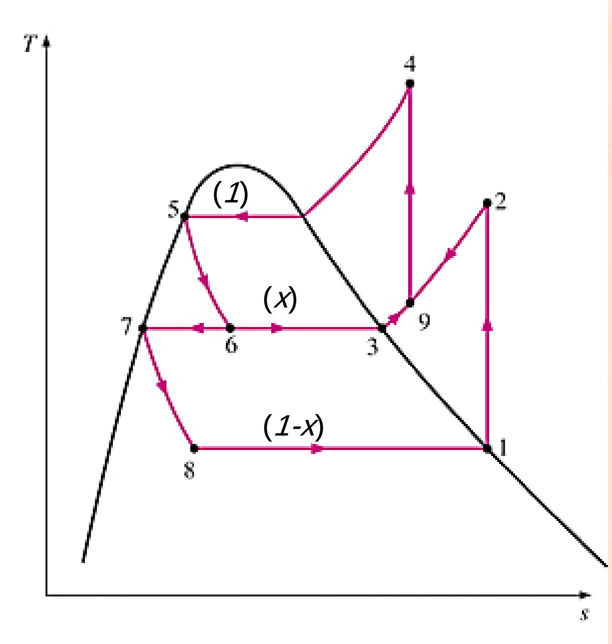
When the fluid used throughout the cascade refrigeration system is the same, the heat exchanger between the stages can be replaced by a mixing chamber (called a *flash chamber*) since it has better heat transfer characteristics.



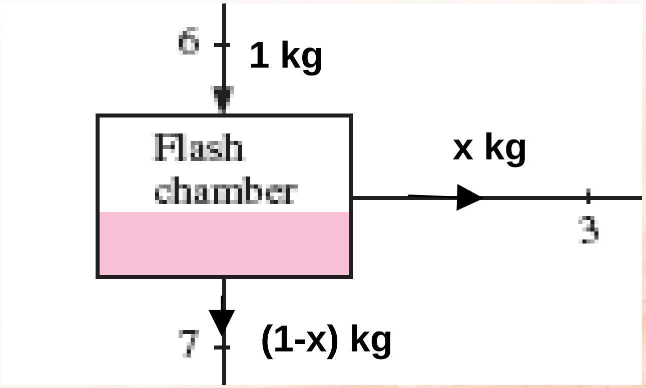
Multistage Compression Refrigeration Systems

- The liquid refrigerant expands in the first expansion valve to the flash chamber pressure, same as the compressor inter-stage pressure.
- Part of the liquid vaporizes. This saturated vapor (state 3) is mixed with the superheated vapor from the low-pressure compressor (state 2), and the mixture enters the high-pressure compressor at state 9.
- The saturated liquid (state 7) expands through the second expansion valve into the evaporator, where it picks up heat from the refrigerated space.





AMOUNT OF VAPOR BLED OFF



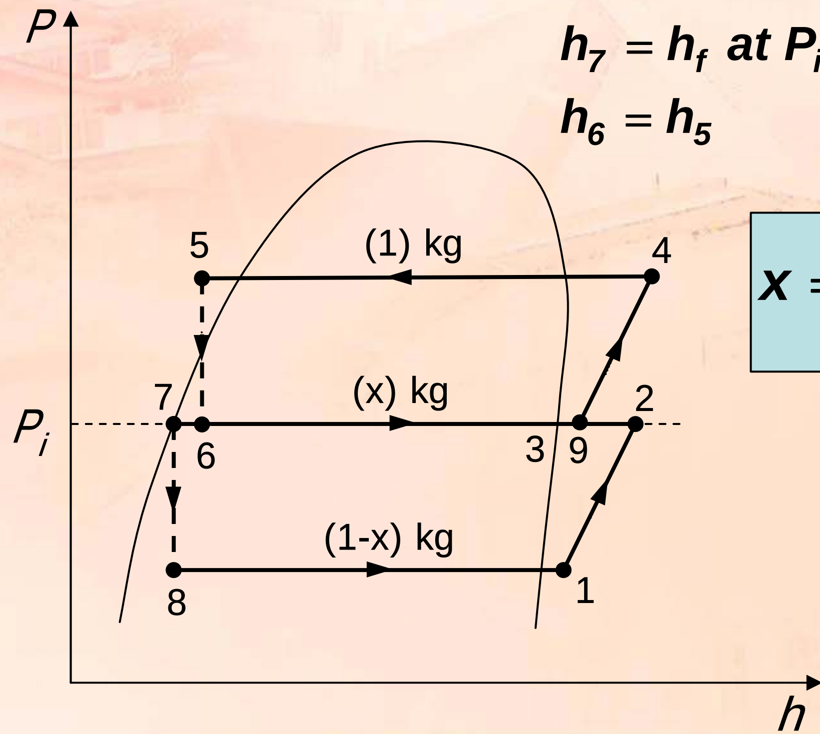
Applying energy balance for the flash chamber

$$h_6 = xh_3 + (1 - x)h_7$$

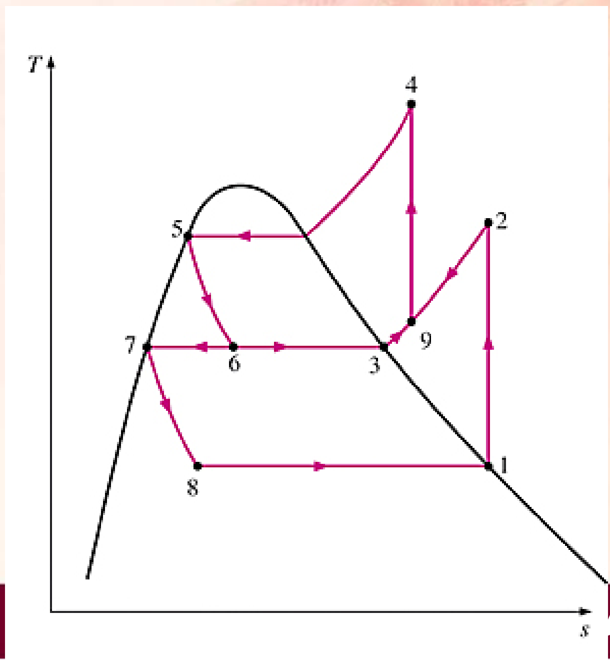
$$h_3 = h_g \text{ at } P_i$$

$$h_7 = h_f \text{ at } P_i$$

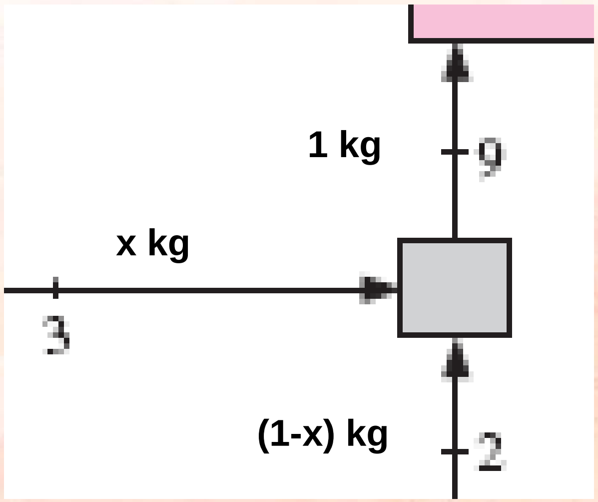
$$h_6 = h_5$$

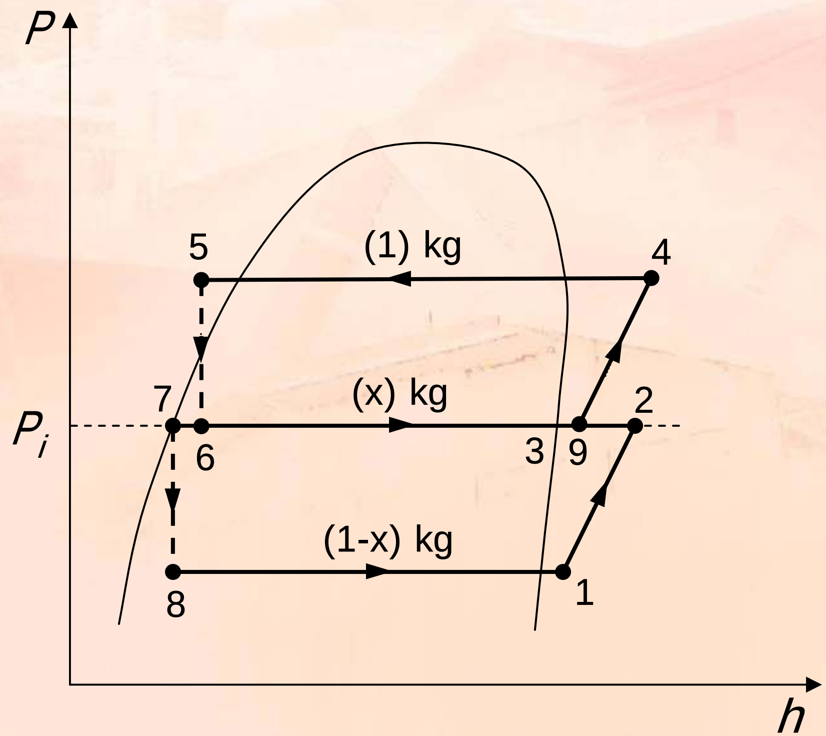


$$x = x_6 = \frac{h_6 - h_{fi}}{h_{fgi}}$$



SFEE AT BRANCH 2, 3 AND 9





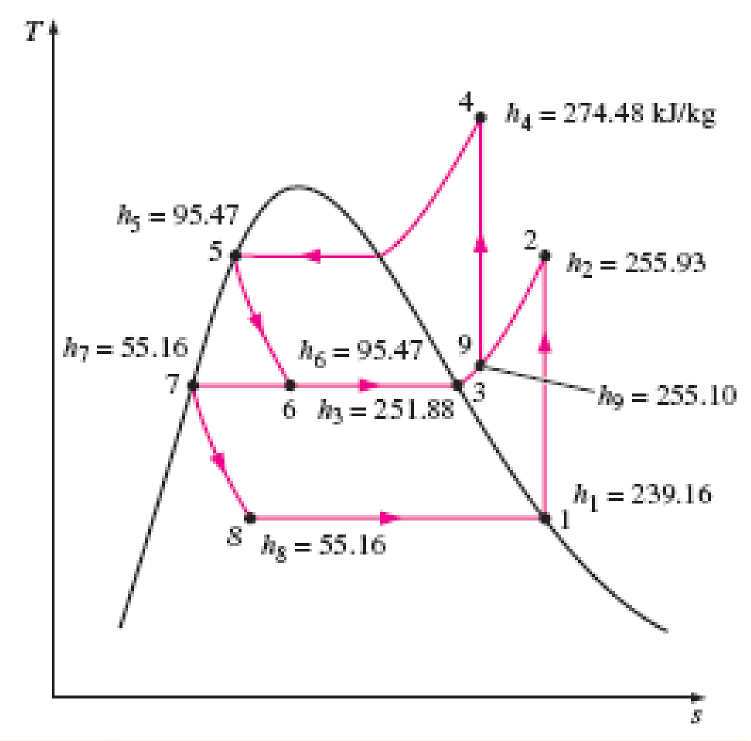
Energy balance,

$$1h_9 = xh_3 + (1 - x)h_2$$

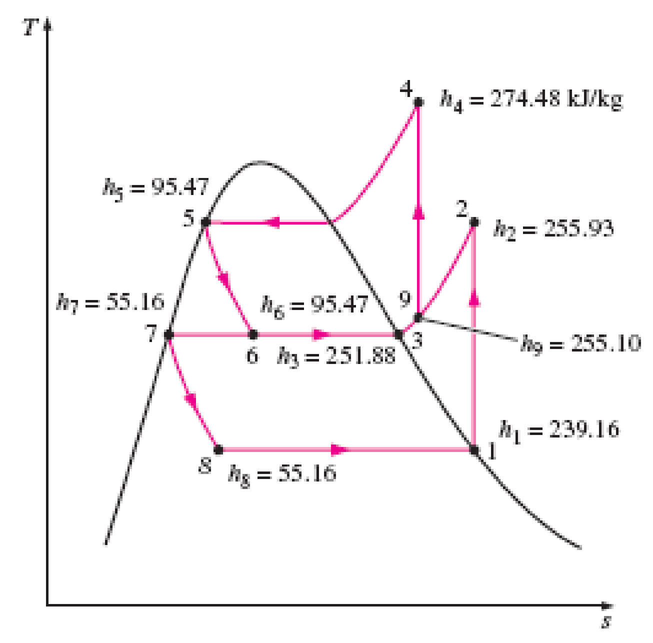
$$h_9 = h_2 - x(h_2 - h_3)$$

EXAMPLE 11-4

Consider a two stage compression refrigeration system operating between the pressure limits of 0.8 MPa and 0.14 MPa. The working fluid is refrigerant 134a. The refrigerant leaves the condenser as a saturated liquid and is throttled to a flash chamber operating at 0.32 MPa. Part of the refrigerant evaporates during this flashing process and this vapor is mixed with the refrigerant leaving the low pressure compressor. The liquid in the flash chamber is throttled to the evaporator pressure and cools the refrigerated space as it vaporizes in the evaporator. Assuming the refrigerant leaves the evaporator as a saturated vapor and both compressor are isentropic, determine (a) the fraction of the refrigerant that evaporates as it is throttled to the flash chamber (b) the amount of heat removed from the refrigerated space and the compressor work per unit mass of refrigerant flowing through the condenser and (c) the COP of the refrigeration system.



EXAMPLE 11-4



(a) $h_5 = h_6 = h_{f\,@\,0.14\,MPa} = 95.47$ kJ/kg

$h_7 = h_8 = h_{f\,@\,0.32\,MPa} = 55.16$ kJ/kg

$$x_6 = \frac{h_6 - h_f}{h_{fg}} = \frac{95.47 - 55.16}{196.71} = 0.2049$$

(b) $q_L = (1 - X)(h_1 - h_8)$

$= (1 - 0.2049)(239.16 - 55.16)$

$= 146.3$ kJ/kg

$E_{in} = E_{out} \Rightarrow (1)h_9 = x_6 h_3 + (1 - x_6)h_2$

$h_9 = (0.2049)(251.88) + (1 - 0.2049)(255.93) = 255.10$ kJ/kg

$w_{in} = w_{comp\,1} + w_{comp\,11}$

$= (1 - x_6)(h_2 - h_1) + (1)(h_4 - h_9)$

$= (1 - 0.2049)(255.93 - 239.16) + (274.48 - 255.10) = 32.71$ kJ/kg

(c) $$COP_R = \frac{q_L}{w_{net,in}} = \frac{146.3}{32.71} = 4.47$$

Assignment 8

A vapour compression refrigeration plant, which uses refrigerant-134a operates at an evaporator pressure of 240 kPa and a condenser pressure of 1.2 MPa. The refrigerant leaves the evaporator at 0^{o}C and exits the condenser at 40^{o}C. The two-stage compression is isentropic. The refrigerant that leaves the condenser is throttled to a flash chamber with a saturation temperature of 15.71^{o}C. Saturated vapour is extracted from the flash chamber and mixes with the refrigerant that leaves the low-pressure compressor, before entering the high-pressure compressor. Saturated liquid from the flash chamber is throttled to the evaporator. If the refrigeration load is 500 kW, determine the:

a) mass flow rate of refrigerant through the condenser (kg/s),
b) mass flow rate of refrigerant extracted from the flash chamber (kg/s)
c) Power required by the low pressure compressor (kW).

Sketch the cycle on a *p-h* diagram.

Problem 11-44

A two-stage compression refrigeration system operates with refrigerant-134a between the pressure limits of 1 and 0.14 MPa. The refrigerant leaves the condenser as a saturated liquid and is throttled to a flash chamber operating at 0.5 MPa. The refrigerant leaving the low-pressure compressor at 0.5 MPa is also routed to the flash chamber. The vapor in the flash chamber is then compressed to the condenser pressure by the high-pressure compressor, and the liquid is throttled to the evaporator pressure. Assuming the refrigerant leaves the evaporator as saturated vapor at a rate of 0.25 kg/s and that both compressors are isentropic, determine the:

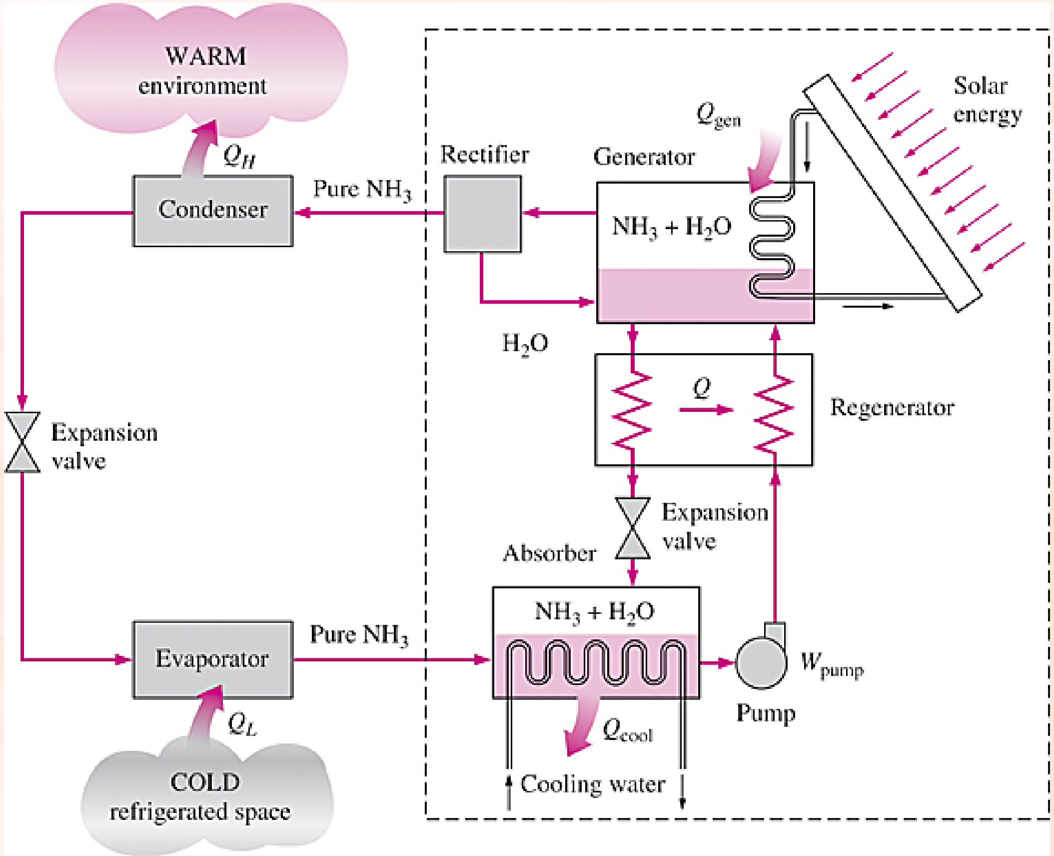
a) fraction of the refrigerant that evaporates in the flash chamber,
b) rate of heat removed from the refrigerated space, and
c) coefficient of performance.

Problem 4

A two-stage cascade refrigeration system operates between pressure limits of 1.2 MPa and 200 kPa with refrigerant-134a as the working fluid. Saturated liquid refrigerant leaving the condenser is throttled to a flash chamber operating at 0.4 MPa. The vapor from the flash chamber is mixed with the refrigerant leaving the low-pressure compressor. The mixture is then compressed to the condenser pressure by the high-pressure compressor. The liquid in the flash chamber is throttled to the evaporator pressure. The mass flow rate of the refrigerant is 0.15 kg/s. Assuming saturated vapor refrigerant leaves the evaporator and the isentropic efficiency is 80 percent for both compressors, determine the:

a) mass flow rate of refrigerant in the high-pressure compressor,
b) rate of heat removal from the refrigerated space, and
c) coefficient of performance of the system.
d) rate of heat removal and the COP if this refrigerator operated on a single-stage cycle between the same pressure limits with the same compressor efficiency and flow rate as in part (a).

ABSORPTION REFRIGERATION SYSTEMS



Ammonia absorption refrigeration cycle.

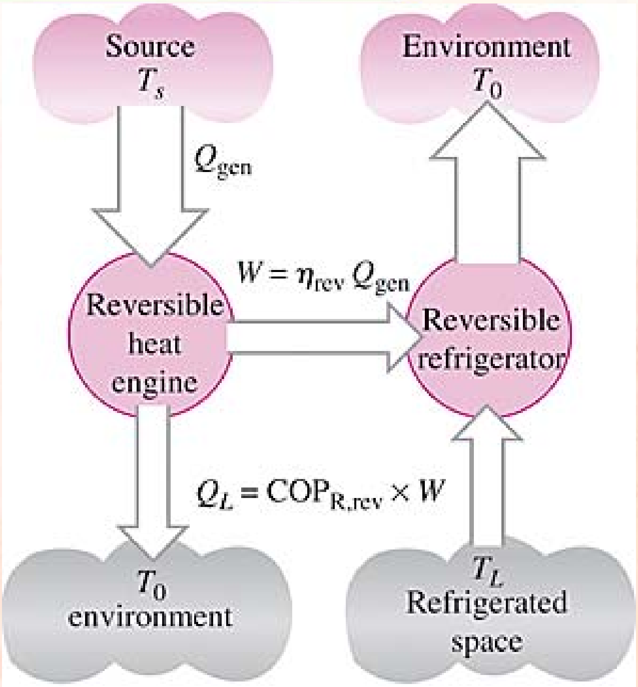
When there is a source of inexpensive thermal energy at a temperature of 100 to 200°C is absorption refrigeration.

Some examples include geothermal energy, solar energy, and waste heat from cogeneration or process steam plants, and even natural gas when it is at a relatively low price.

ABSORPTION REFRIGERATION SYSTEMS

- Absorption refrigeration systems (ARS) involve the absorption of a *refrigerant* by a *transport medium*. The most widely used system is the ammonia–water system, where ammonia (NH_3) serves as the refrigerant and water (H_2O) as the transport medium.
- Other systems include water–lithium bromide and water–lithium chloride systems, where water serves as the refrigerant. These systems are limited to applications such as A-C where the minimum temperature is above the freezing point of water.
- Compared with vapor-compression systems, ARS have one major advantage: A liquid is compressed instead of a vapor and as a result the work input is very small (on the order of one percent of the heat supplied to the generator) and often neglected in the cycle analysis.
- ARS are much more expensive than the vapor-compression refrigeration systems. They are more complex and occupy more space, they are much **less efficient** thus requiring much larger cooling towers to reject the waste heat, and they are more **difficult to service** since they are less common.
- Therefore, ARS should be considered only when the unit cost of thermal energy is low and is projected to remain low relative to electricity.
- ARS are primarily used in large commercial and industrial installations.

ABSORPTION REFRIGERATION SYSTEMS



$$W = \eta_{rev} Q_{gen} = \left(1 - \frac{T_0}{T_s}\right) Q_{gen}$$

$$Q_L = COP_{R,rev} W = \left(\frac{T_L}{T_0 - T_L}\right) W$$

$$COP_{rev,absorption} = \frac{Q_L}{Q_{gen}} = \left(1 - \frac{T_0}{T_s}\right)\left(\frac{T_L}{T_0 - T_L}\right)$$

$$COP_{absorption} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{Q_{gen} + W_{pump,in}} \cong \frac{Q_L}{Q_{gen}}$$

The COP of actual absorption refrigeration systems is usually less than unity.

Air-conditioning systems based on absorption refrigeration, called the *absorption chillers,* perform best when the heat source can supply heat at a high temperature with little temperature drop.

THE END