ENGINEERING THERMODYNAMICS -II

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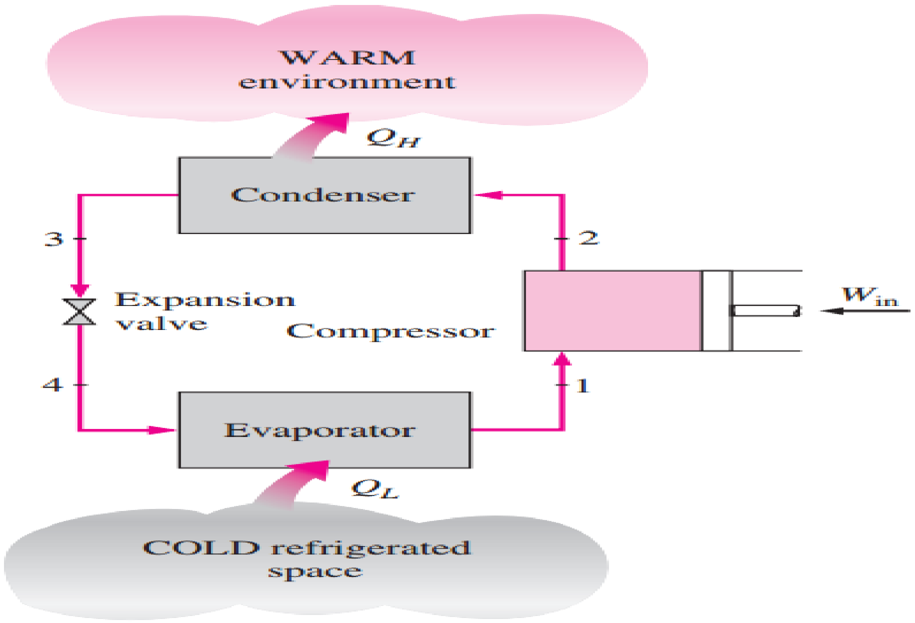

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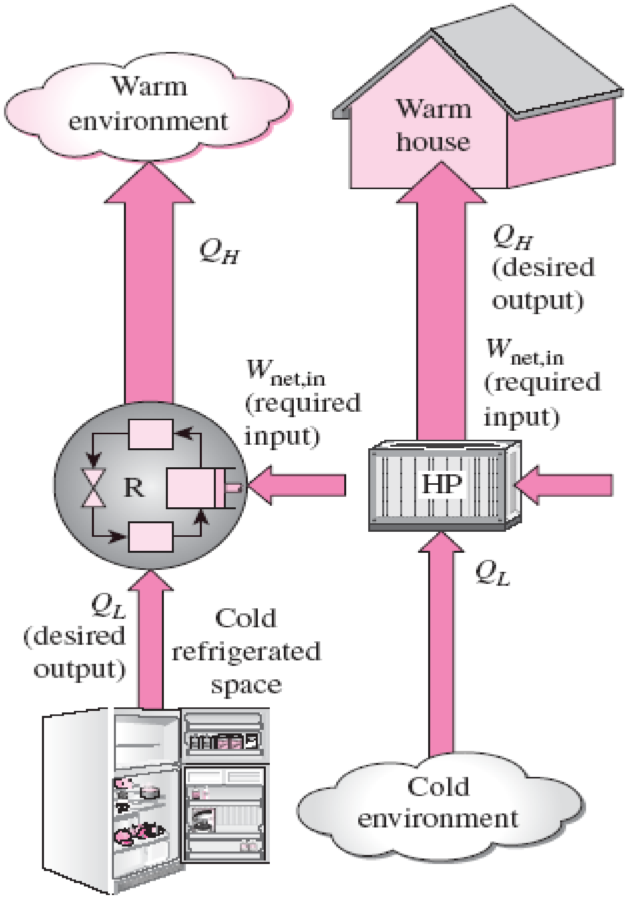
5. Refrigeration Cycles

Refrigerators and Heat pumps

The vapor compression refrigeration cycle is a common method for transferring heat from a low temperature to a high temperature.

REFRIGERATORS



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

- The transfer of heat from a low-temperature region to a high-temperature one requires special devices called **refrigerators**.
- Refrigerators are cyclic device, and the working fluids used in the refrigeration cycles are called **refrigerants**.

HEAT PUMPS

- Another device that transfers heat from a low-temperature medium to a high-temperature one is the **heat pump**.
- In general, the term heat pump is used to describe the cycle as heat energy is removed from the low-temperature space and rejected to the high-temperature space.
- Refrigerators and heat pumps are essentially the same devices; they differ in their objectives only.

- The objective of a **refrigerator** is to remove heat (Q_L) from the cold medium.
- The objective of a **heat pump** is to supply heat (Q_H) to a warm medium.

PURPOSE OF REFRIGERATORS AND HEAT PUMPS

✓The purpose of a refrigerator is the removal of heat, called the cooling load, from a low-temperature medium.

✓The purpose of a heat pump is the transfer of heat to a high-temperature medium, called the heating load.

✓When we are interested in the heat energy removed from a low-temperature space, the device is called a refrigerator.

✓When we are interested in the heat energy supplied to the high-temperature space, the device is called a heat pump.

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

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

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

cont…

❖Both COP_R and COP_{HP} can be larger than 1. Under the same operating conditions, the COPs are related by

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

❑The *cooling capacity* of a refrigeration system – is the rate of heat removal from the refrigeration space – is often expressed in terms of **ton of refrigeration.**

❑The capacity of a refrigeration system that can freeze 1 ton of liquid water at 0 °C into ice at 0 °C in 24 h is said to be **1 ton**.

Reversed Carnot Refrigerator and Heat Pump

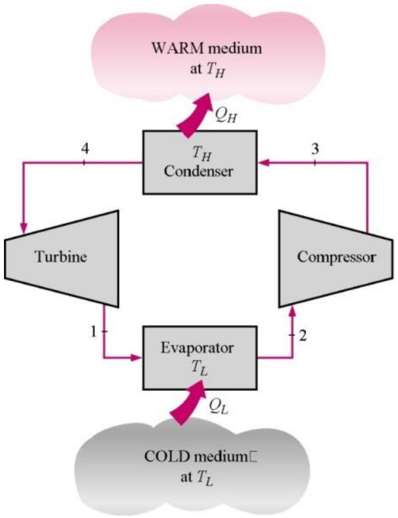
➢Shown below are the cyclic refrigeration device operating between two constant temperature reservoirs and the *T-s* diagram for the working fluid when the reversed Carnot cycle is used.

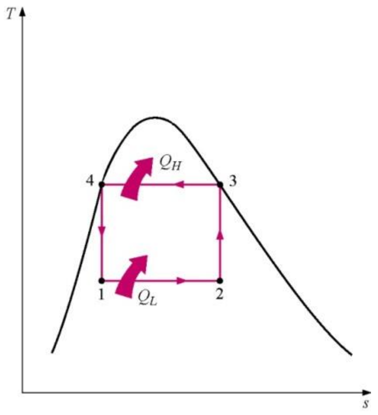
➢Recall that in the Carnot cycle heat transfers take place at constant temperature.

➢If our interest is the cooling load, the cycle is called the Carnot refrigerator.

➢If our interest is the heat load, the cycle is called the Carnot heat pump.

Reversed Carnot Refrigerator and Heat Pump





- The standard of comparison for refrigeration cycles is the *reversed Carnot cycle.*
- A refrigerator or heat pump that operates on the reversed Carnot cycle is called a *Carnot refrigerator* or a *Carnot heat pump,* and their COPs are

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

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

VAPOR-COMPRESSION REFRIGERATION CYCLE

The vapor-compression refrigeration cycle has four components: evaporator, compressor, condenser, and expansion (or throttle) valve.

○The most widely used refrigeration cycle is the *vapor-compression refrigeration cycle.*

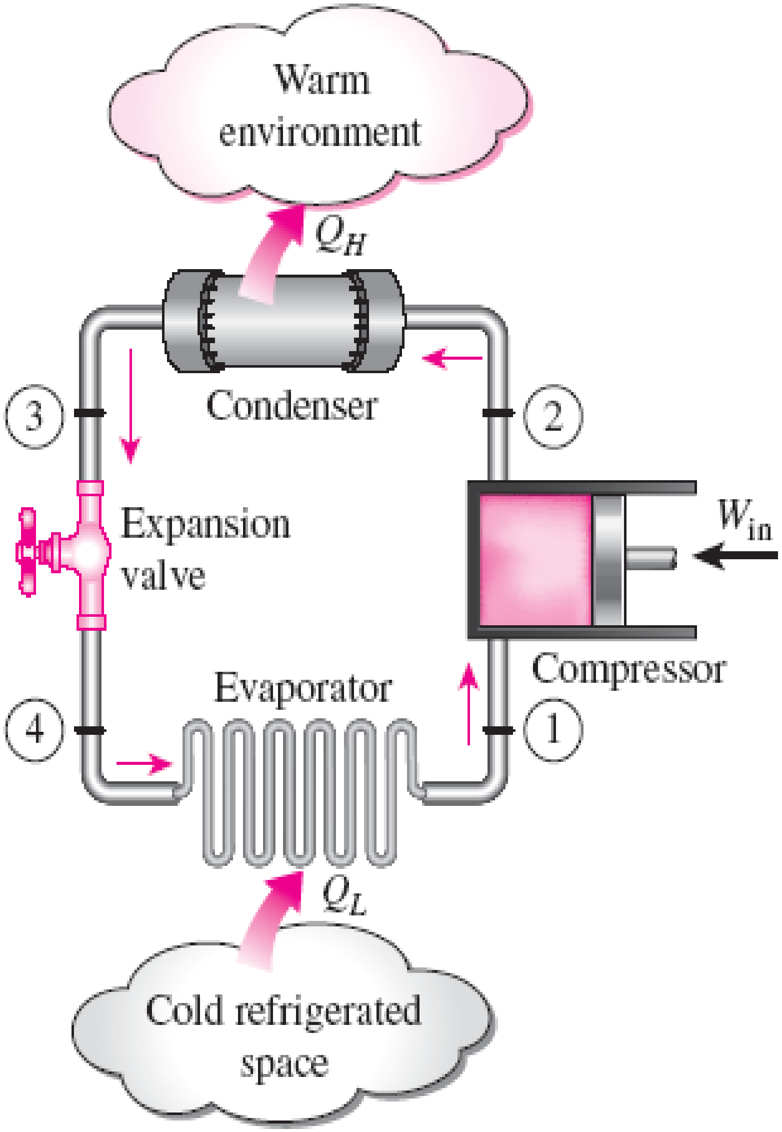
○ In an ideal vapor-compression refrigeration cycle, the refrigerant enters the compressor as a saturated vapor and is cooled to the saturated liquid state in the condenser.

○It is then throttled to the evaporator pressure and vaporizes as it absorbs heat from the refrigerated space.

Two modes of operations:

1. Ideal vapor-compression refrigeration cycle
2. Actual vapor-compression refrigeration cycle

IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE



❖The **vapor-compression refrigeration cycle** is the ideal model for refrigeration systems, air conditions and heat pumps.

It consist of four processes:

1-2 Isentropic compression in compressor.

2-3 Constant-pressure heat rejection in a condenser.

3-4 Throttling in an expansion devise.

4-1 Constant-pressure heat absorption in an evaporator.

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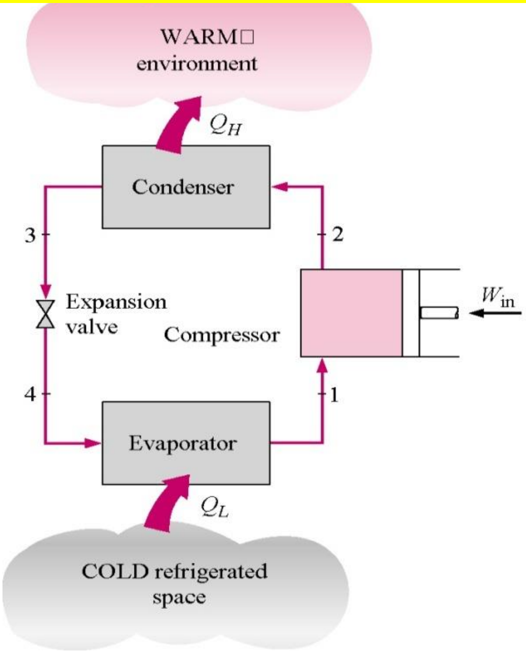
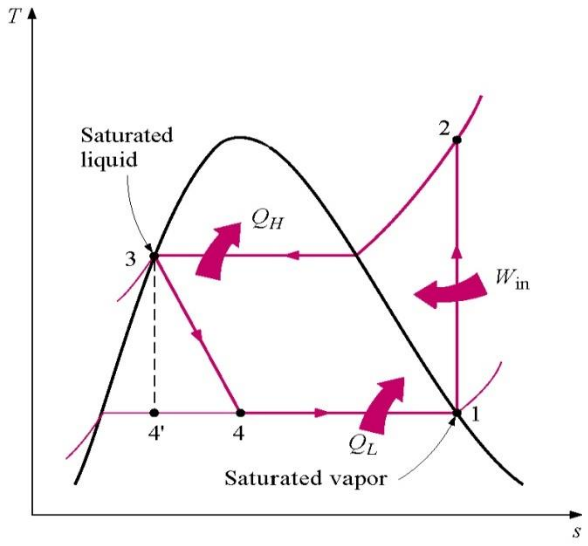
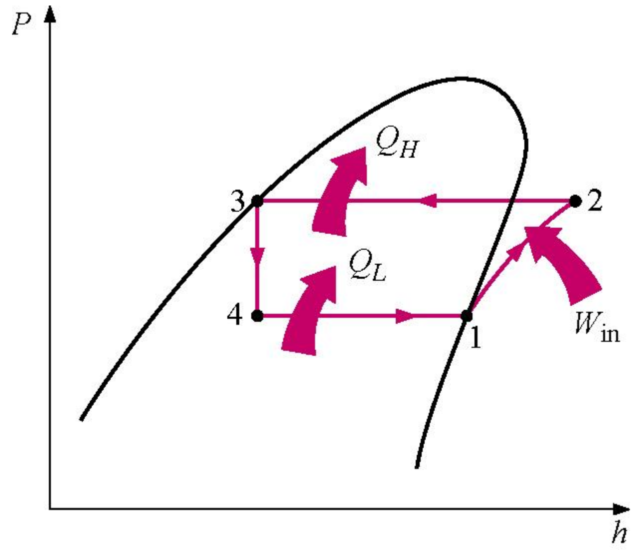




The *P-h* diagram is another convenient diagram often used to illustrate the refrigeration cycle.



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The process in ideal vapor compression refrigeration cycle:

✓The refrigerant enters the compressor at state **1** as **saturated vapor** and is compressed isentropically to the condenser pressure.

✓The temperature of the refrigerant increases during this isentropic compression process to well above the temperature of the surrounding medium.

✓The refrigerant then enters the condenser as **superheat vapor** at state **2** and leaves as **saturated liquid** at state **3** as a result to the heat rejection to the surrounding.

✓The saturated liquid at state 3 enters an expansion valve or capillary tube and leaves at evaporator pressure.

✓The temperature of refrigerant drop below the temperature of refrigerated space during this stage.

✓The refrigerant enters the evaporator at stage **4** as saturated mixture and it completely evaporate by absorbing the heat from the refrigerated space.

✓The refrigerant leaves the evaporator as **saturated vapor** and reenters the compressor, completing the cycle.

cont…

- ✓The ideal vapor compression refrigeration cycle is not an internally reversible cycle since it involves an irreversible (throttling) process.
- ✓This process is maintained in the cycle to make it a more realistic model for the actual vapor-compression refrigeration cycle.
- ✓If the throttling device were replaced by an isentropic turbine, the refrigerant would enter the evaporator at state 4’ instead of state 4.
- ✓As a result, the refrigeration capacity would increase (by the area under process curve 4’-4) and the net work input would decrease (by the amount of work output of the turbine).
- ✓Replacing the expansion valve by a turbine is not practical, however, since the added benefits cannot justify the added cost and complexity.

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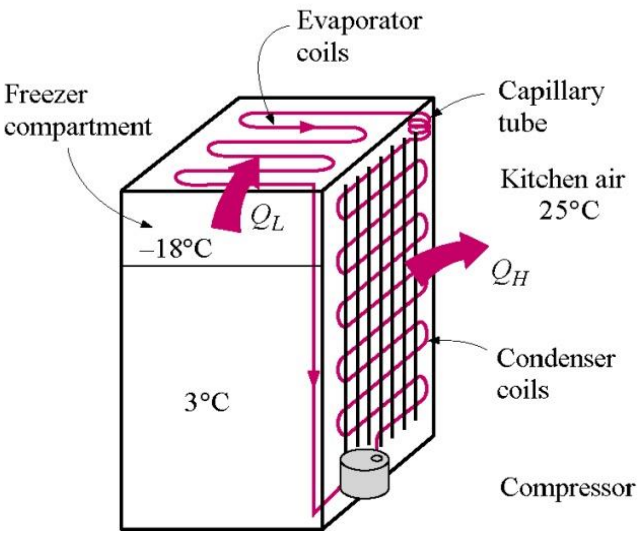
The ordinary household refrigerator is a good example of the application of this cycle.



Results of First and Second Law Analysis for Steady-Flow

Component	Process	First Law Result
Compressor	$s = \text{const.}$	$\dot{W}_{in} = \dot{m}(h_2 - h_1)$
Condenser	$P = \text{const.}$	$\dot{Q}_H = \dot{m}(h_2 - h_3)$
Throttle Valve	$\Delta s > 0$ $\dot{W}_{net} = 0$ $\dot{Q}_{net} = 0$	$h_4 = h_3$
Evaporator	$P = \text{const.}$	$\dot{Q}_L = \dot{m}(h_1 - h_4)$

$$COP_R = \frac{\dot{Q}_L}{\dot{W}_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

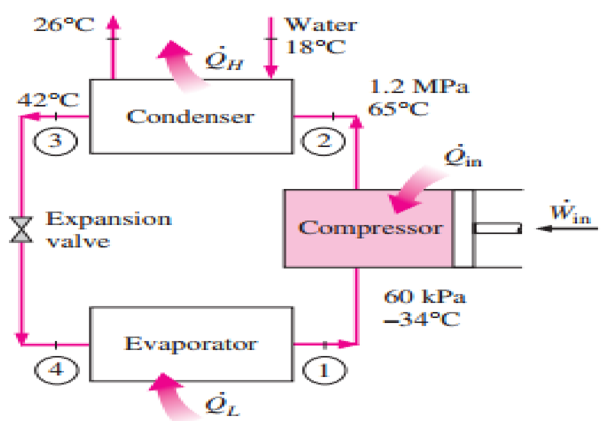
$h_1 = h_{g\,@\,P_1}$ and $h_3 = h_{f\,@\,P_3}$ for the ideal case

Example 5.1

Refrigerant-134a is the working fluid in an ideal compression refrigeration cycle. The refrigerant leaves the evaporator at -20°C and has a condenser pressure of 0.9 MPa. The mass flow rate is 3 kg/min. Find COP_R and $COP_{R,\ Carnot}$ for the same T_{max} and T_{min}, and the tons of refrigeration.

Assignment 5.1

A commercial refrigerator with refrigerant-134a as the working fluid is used to keep the refrigerated space at -30°C by rejecting its waste heat to cooling water that enters the condenser at 18°C at a rate of 0.25 kg/s and leaves at 26°C. The refrigerant enters the condenser at 1.2 MPa and 65°C and leaves at 42°C. The inlet state of the compressor is 60 kPa and -34°C and the compressor is estimated to gain a net heat of 450 W from the surroundings. Determine (*a*) the quality of the refrigerant at the evaporator inlet, (*b*) the refrigeration load, (*c*) the COP of the refrigerator, and (*d*) the theoretical maximum refrigeration load for the same power input to the compressor.



ACTUAL VAPOR-COMPRESSION REFRIGERATION CYCLE

➢An actual vapor-compression refrigeration cycle differs from the ideal one owing mostly to the irreversibilities that occur in various components, mainly due to fluid friction (causes pressure drops) and heat transfer to or from the surroundings.

➢The COP decreases as a result of irreversibilities

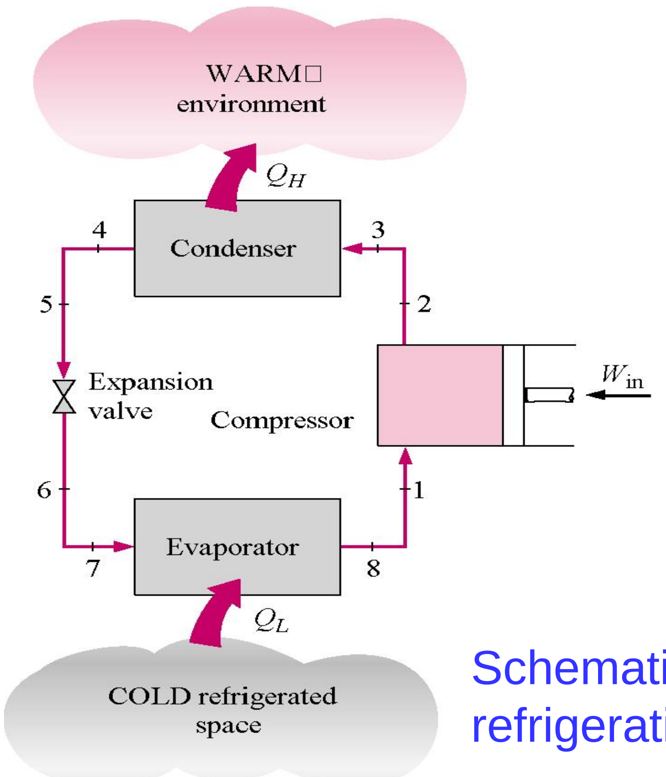
DIFFERENCES

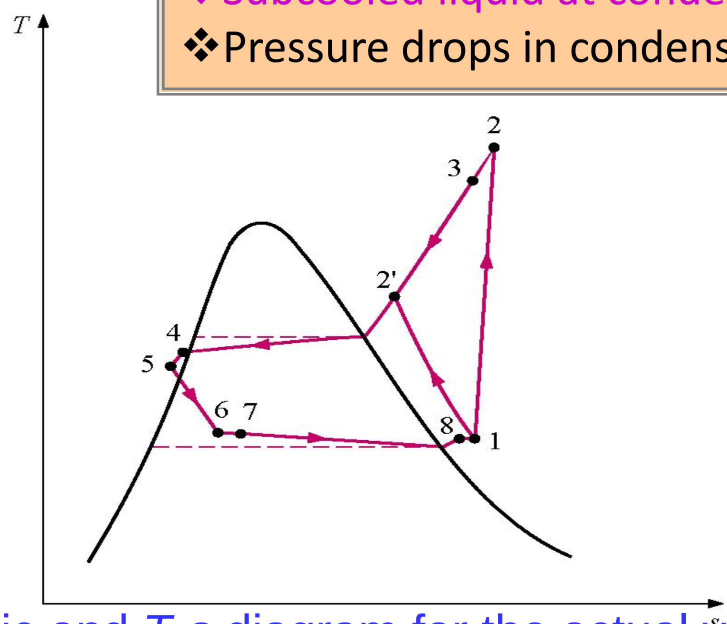
❖Non-isentropic compression

❖Superheated vapor at evaporator exit

❖Subcooled liquid at condenser exit

❖Pressure drops in condenser and evaporator





Schematic and *T*-*s* diagram for the actual vapor-compression refrigeration cycle.

Example 5.2

Refrigerant-134a enters the compressor of a refrigerator as superheated vapor at 0.14MPa and -10°C at a rate of 0.05 kg/s, and it leaves at 0.8MPa and 50°C. The refrigerant is cooled in the condenser to 27°C and 0.72MPa, and it is throttled to 0.15MPa. 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 and the power input to the compressor, (*b*) the isentropic efficiency of the compressor, and (*c*) the COP of the refrigerator.

Assignment 5.2

Refrigerant-134a enters the compressor of a refrigerator at 140 kPa and -10°C at a rate of 0.3 m^3/min and leaves at 1MPa. The isentropic efficiency of the compressor is 78 percent. The refrigerant enters the throttling valve at 0.95 Mpa and 30°C and leaves the evaporator as saturated vapor at -18.5°C. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the power input to the compressor, (*b*) the rate of heat removal from the refrigerated space, and (*c*) the pressure drop and rate of heat gain in the line between the evaporator and the compressor.

SELECTING THE RIGHT REFRIGERANT

- Refrigerant selection is based on several factors:
  ►Performance: provides adequate cooling capacity cost-effectively.
  ►Safety: avoids hazards (i.e., toxicity).
  ►Environmental impact: minimizes harm to stratospheric ozone layer and reduces negative impact to global climate change.
- Two important parameters that need to be considered in the selection of a refrigerant are the temperatures of the two media (the refrigerated space and the environment) with which the refrigerant exchanges heat.

- Several refrigerants may be used in refrigeration systems such as chlorofluorocarbons (CFCs), ammonia, hydrocarbons (propane, ethane, ethylene, etc.), carbon dioxide, air (in the air-conditioning of aircraft), and even water (in applications above the freezing point).
- R-11, R-12, R-22, R-134a, and R-502 account for over 90 percent of the market.
- The industrial and heavy-commercial sectors use *ammonia* (it is toxic).
- R-11 is used in large-capacity water chillers serving A-C systems in buildings.
- R-134a (replaced R-12, which damages ozone layer) is used in domestic refrigerators and freezers, as well as automotive air conditioners.
- R-22 is used in window air conditioners, heat pumps, air conditioners of commercial buildings, and large industrial refrigeration systems, and offers strong competition to ammonia.
- R-502 (a blend of R-115 and R-22) is the dominant refrigerant used in commercial refrigeration systems such as those in supermarkets.

Heat Pump Systems

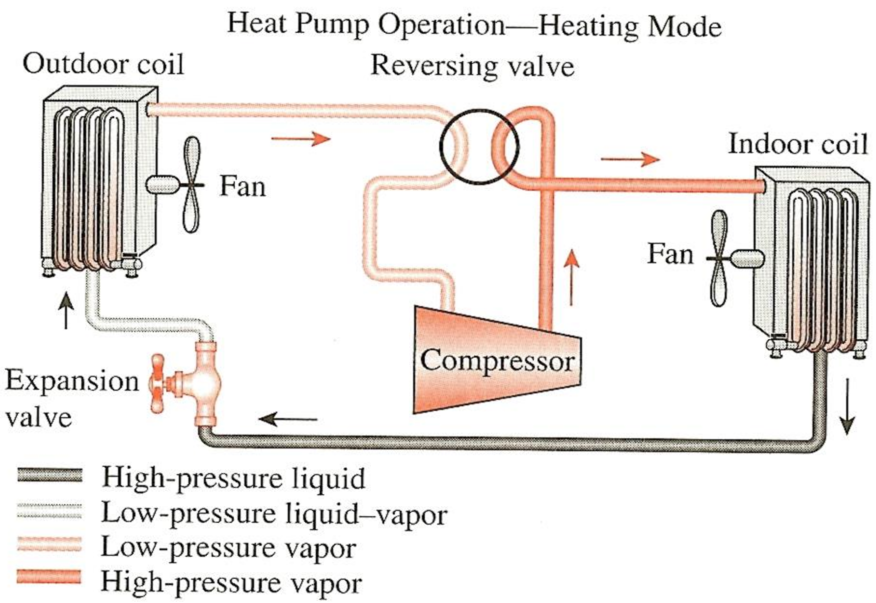
A typical heat pump system is shown here.

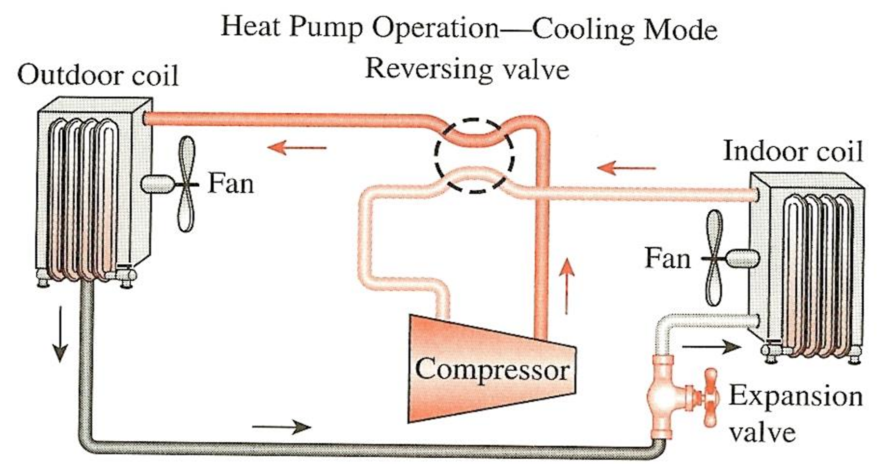
❖ In the heating mode high-pressure vapor refrigerant is sent to the indoor heat exchanger coil.

❖The refrigerant gives up its energy to the inside air and condenses to a high-pressure liquid.

❖The liquid is throttled to a low-pressure, low-temperature liquid-vapor in the outdoor coil and receives energy from the from the outside air.

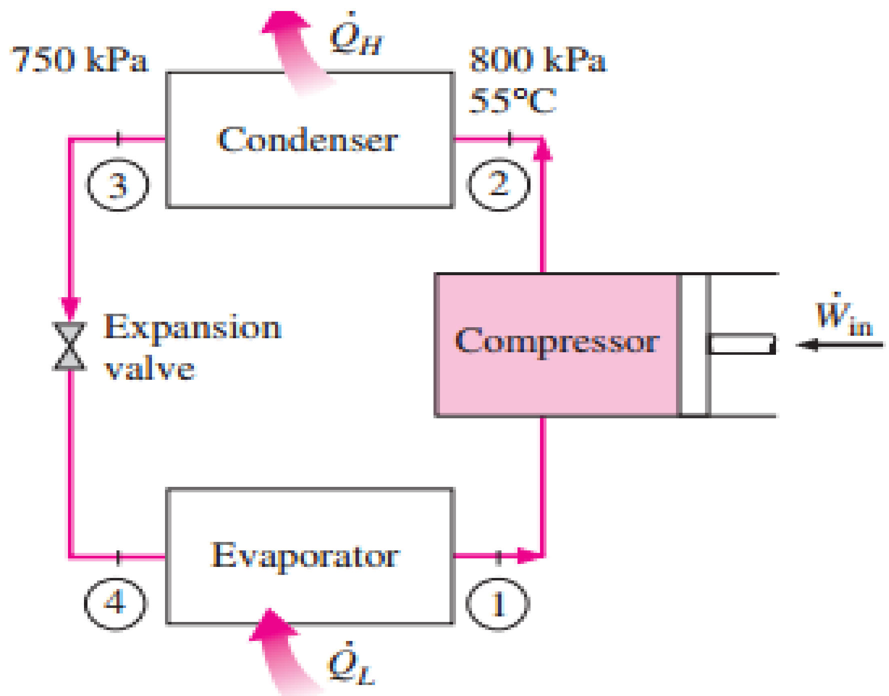
❖The refrigerant vaporizes, enters the compressor as a low-pressure vapor to be compressed to the high-pressure, and the cycle is completed.





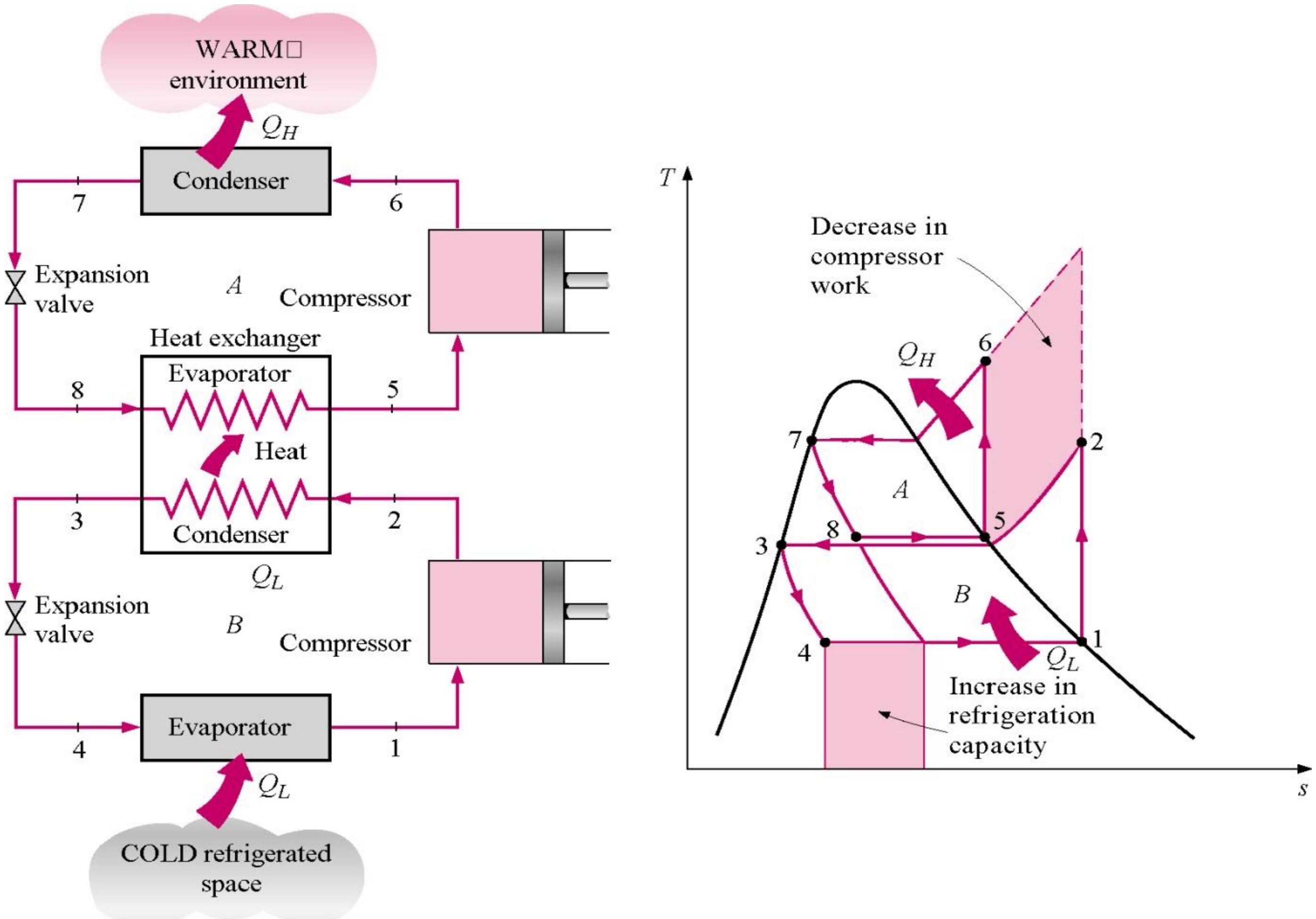
Assignment 5.3

Refrigerant-134a enters the condenser of a residential heat pump at 800 kPa and 55°C at a rate of 0.018 kg/s and leaves at 750 kPa subcooled by 3°C. The refrigerant enters the compressor at 200 kPa superheated by 4°C. Determine (*a*) the isentropic efficiency of the compressor, (*b*) the rate of heat supplied to the heated room, and (*c*) the COP of the heat pump. Also, determine (*d*) the COP and the rate of heat supplied to the heated room if this heat pump operated on the ideal vapor-compression cycle between the pressure limits of 200 and 800 kPa.



Cascade refrigeration systems

➢Very low temperatures can be achieved by operating two or more vapor compression systems in series, called ***cascade* refrigeration cycles**
The COP of a refrigeration system also increases as a result of cascading.



Cascade refrigeration systems

- The two cycles are connected through the heat exchanger in the middle, which serves as the evaporator for the topping cycle (cycle *A*) and the condenser for the bottoming cycle (cycle *B*).
- 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

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

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

Example 5.3

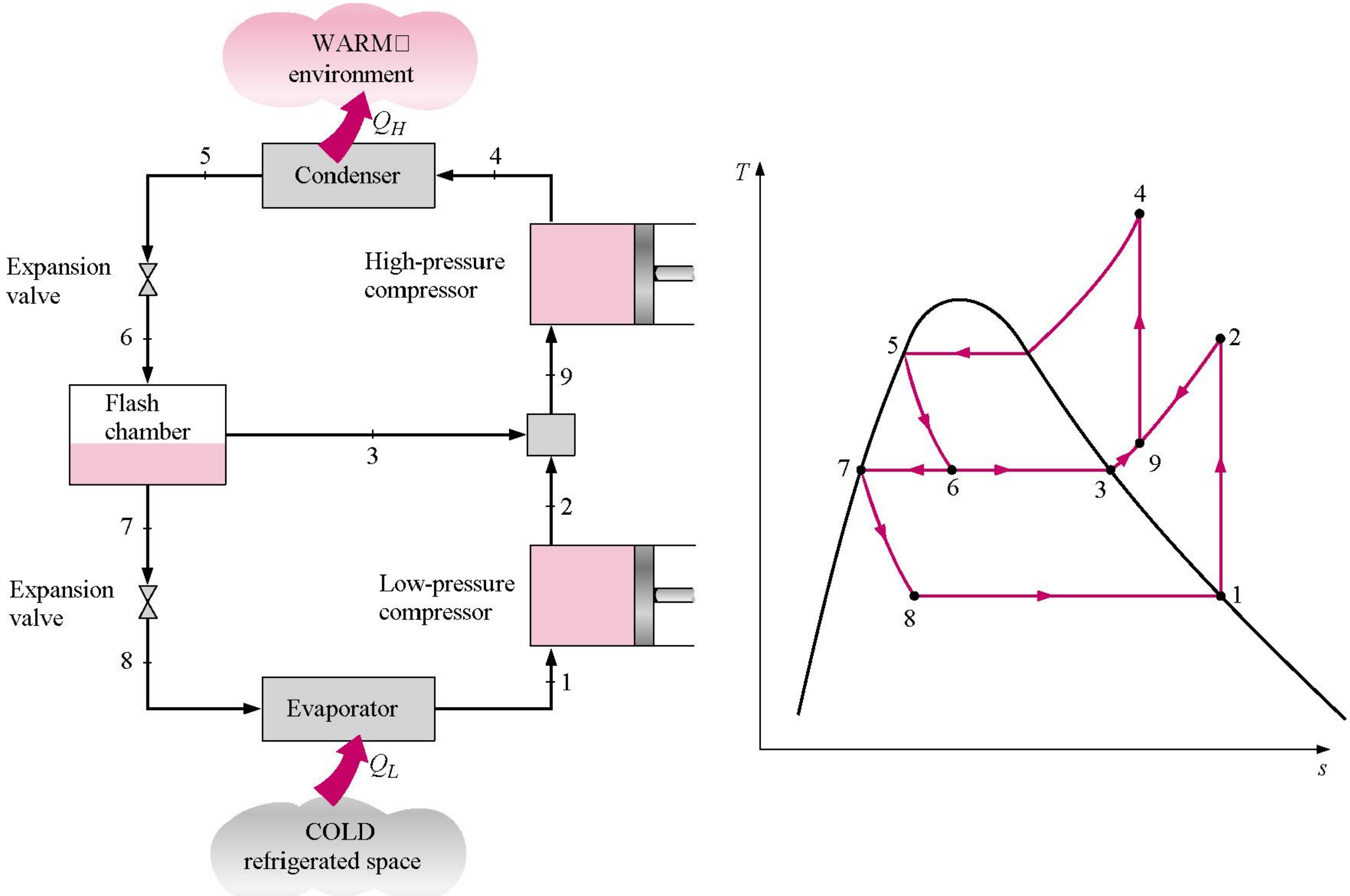
Consider a two-stage cascade refrigeration system operating between the pressure limits of 0.8 and 0.14MPa. Each stage operates on an ideal vapor compression refrigeration cycle with refrigerant-134a as the working fluid. Heat rejection from the lower cycle to the upper cycle takes place in an adiabatic counter flow heat exchanger where both streams enter at about 0.32MPa. (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 coefficient of performance of this cascade refrigerator.

Assignment 5.4

Consider a two-stage cascade refrigeration system operating between the pressure limits of 1.2MPa and 200kPa 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 0.5MPa, 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 (*a*) the mass flow rate of the refrigerant through the upper cycle, (*b*) the rate of heat removal from the refrigerated space, and (*c*) the COP of this refrigerator.

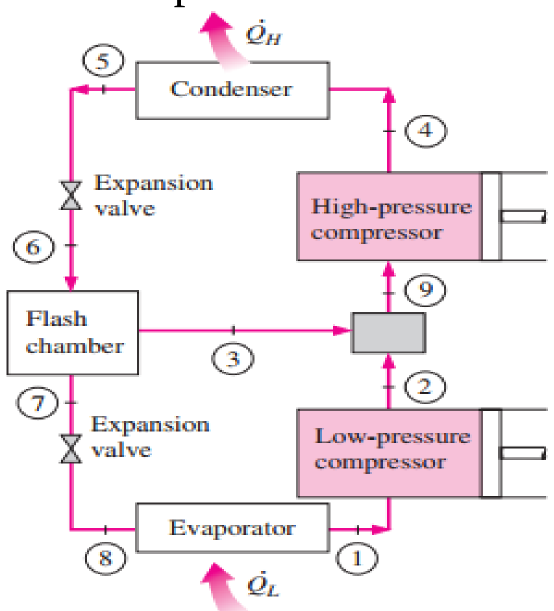
Multistage compression refrigeration systems

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. Such systems are called **multistage compression refrigeration systems.**



Assignment 5.5

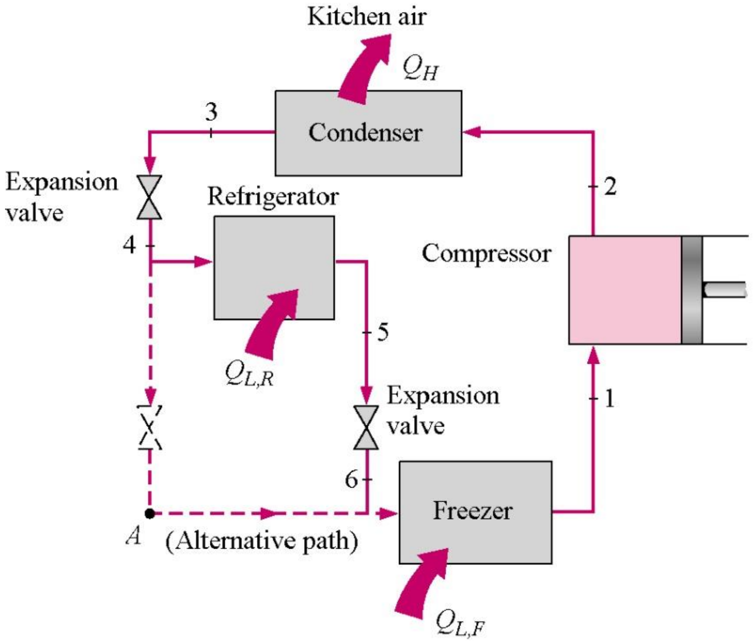
Consider a two-stage cascade refrigeration system operating between the pressure limits of 1.2 MPa and 200 kPa with refrigerant-134a as the working fluid. The refrigerant leaves the condenser as a saturated liquid and is throttled to a flash chamber operating at 0.45 MPa. Part of the refrigerant evaporates during this flashing process, and this vapor 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 and cools the refrigerated space as it vaporizes in the evaporator. The mass flow rate of the refrigerant through the low-pressure compressor is 0.15 kg/s. Assuming the refrigerant leaves the evaporator as a saturated vapor and the isentropic efficiency is 80 percent for both compressors, determine (*a*) the mass flow rate of the refrigerant through the high-pressure compressor, (*b*) the rate of heat removal from the refrigerated space, and (*c*) the COP of this refrigerator. Also, determine (*d*) the 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 the same flow rate as in part (*a*)

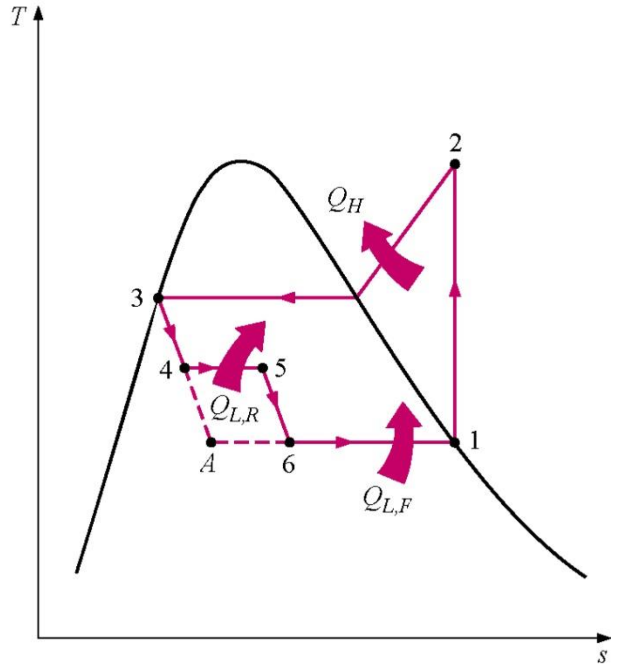


Multipurpose refrigeration systems

❖A refrigerator with a single compressor can provide refrigeration at several temperatures by throttling the refrigerant in stages.

❖Some applications require refrigeration at more than one temperature. This could be accomplished by using a separate throttling valve and a separate compressor for each evaporator operating at different temperatures.



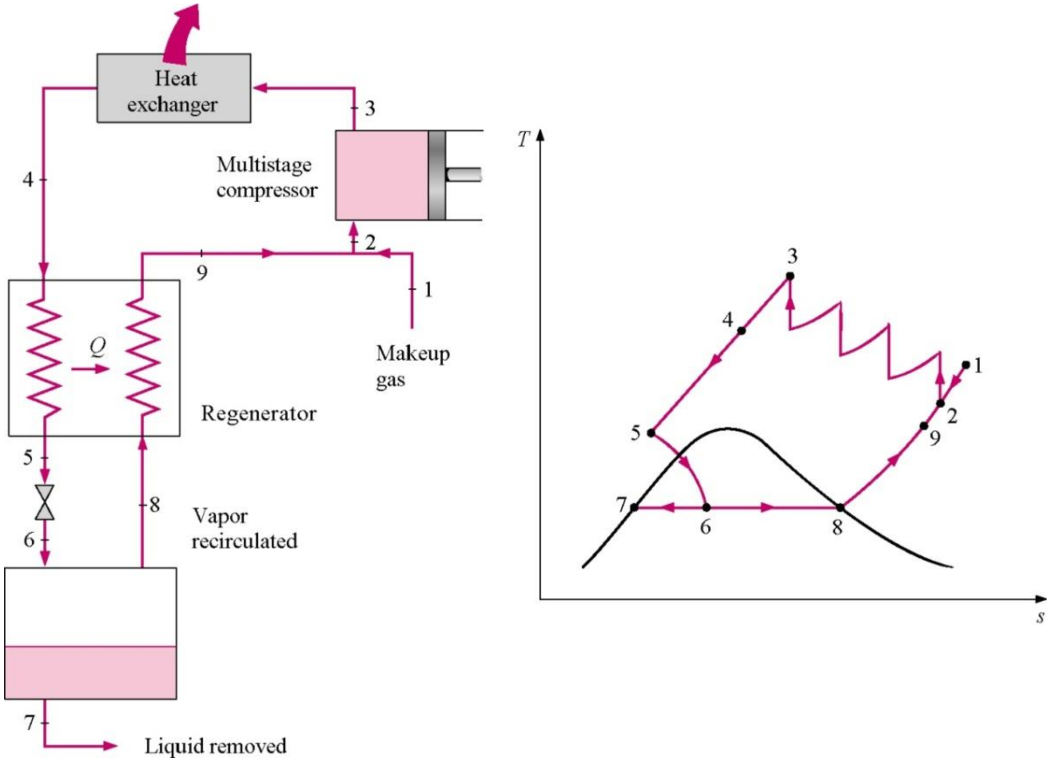


Liquefaction of gases

➢The liquefaction of gases has always been an important area of refrigeration since many important scientific and engineering processes at cryogenic temperatures (temperatures below about -100°C) depend on liquefied gases.

➢Another way of improving the performance of a vapor-compression refrigeration system is by using *multistage compression with regenerative cooling.*

➢The vapor-compression refrigeration cycle can also be used to liquefy gases after some modifications.



Gas Refrigeration Systems

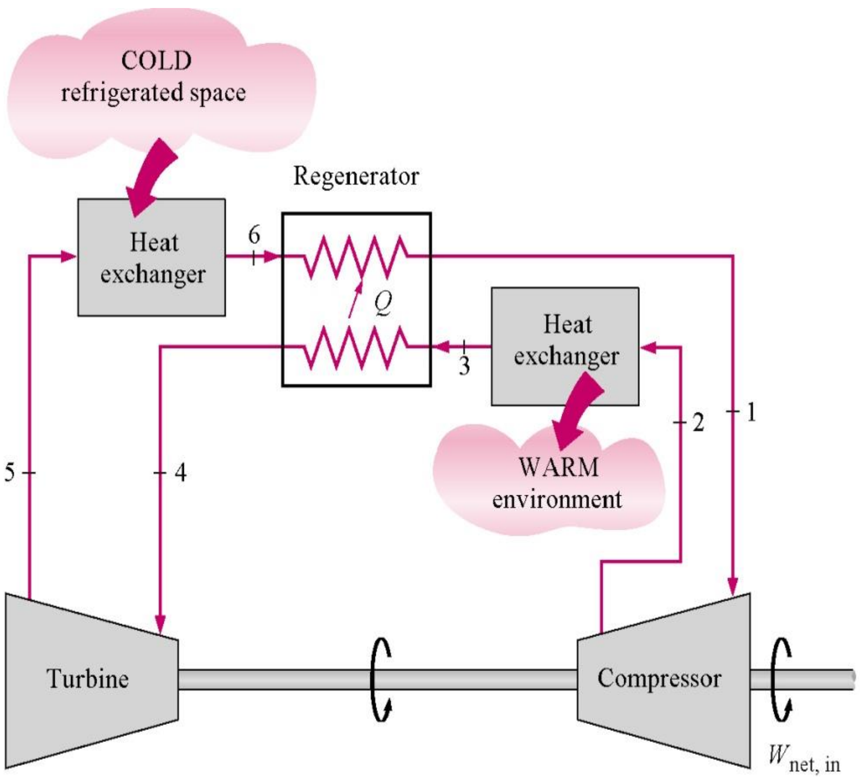
❖The power cycles can be used as refrigeration cycles by simply reversing them. Of these, the *reversed Brayton cycle*, which is also known as the *gas refrigeration cycle*, is used to cool aircraft and to obtain very low (cryogenic) temperatures after it is modified with regeneration.

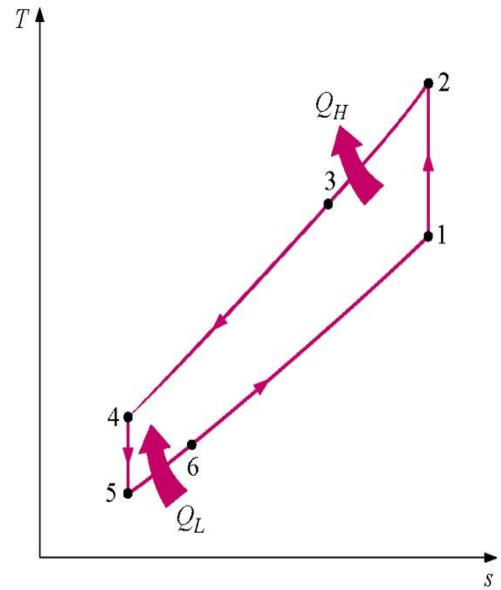
❖ The work output of the turbine can be used to reduce the work input requirements to the compressor.

- The surroundings are at T_0, and the refrigerated space is to be maintained at T_L.
- The gas is compressed during process 1-2.
- The high-pressure, high-temperature gas at state 2 is then cooled at constant pressure to T_0 by rejecting heat to the surroundings.
- This is followed by an expansion process in a turbine, during which the gas temperature drops to T_4.
- Finally, the cool gas absorbs heat from the refrigerated space until its temperature rises to T_1.

Thus, the COP of a gas refrigeration cycle is

$$COP_R = \frac{q_L}{w_{net,in}} = \frac{q_L}{w_{comp,in} - w_{turb,out}}$$





Example 5.4

A gas refrigeration system using air as the working fluid has a pressure ratio of 4. Air enters the compressor at -7°C. The high-pressure air is cooled to 27°C by rejecting heat to the surroundings. It is further cooled to -15°C by regenerative cooling before it enters the turbine. Assuming both the turbine and the compressor to be isentropic and using constant specific heats at room temperature, determine (*a*) the lowest temperature that can be obtained by this cycle, (*b*) the coefficient of performance of the cycle, and (*c*) the mass flow rate of air for a refrigeration rate of 12 kW.

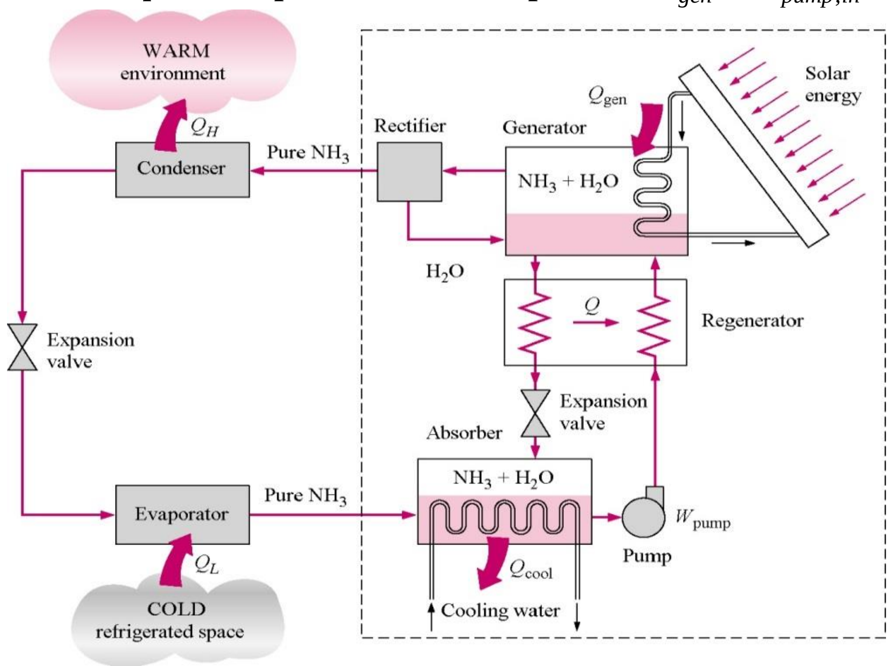
Assignment 5.6

A gas refrigeration system using air as the working fluid has a pressure ratio of 5. Air enters the compressor at 0°C. The high-pressure air is cooled to 35°C by rejecting heat to the surroundings. The refrigerant leaves the turbine at -80°C and then it absorbs heat from the refrigerated space before entering the regenerator. The mass flow rate of air is 0.4 kg/s. Assuming isentropic efficiencies of 80 percent for the compressor and 85 percent for the turbine and using constant specific heats at room temperature, determine (*a*) the effectiveness of the regenerator, (*b*) the rate of heat removal from the refrigerated space, and (*c*) the COP of the cycle. Also, determine (*d*) the refrigeration load and the COP if this system operated on the simple gas refrigeration cycle. Use the same compressor inlet temperature as given, the same turbine inlet temperature as calculated, and the same compressor and turbine efficiencies.

Absorption Refrigeration Systems

- Another form of refrigeration that becomes economically attractive when there is a source of inexpensive heat energy at a temperature of 100 to 200°C is *absorption refrigeration*, where the refrigerant is absorbed by a transport medium and compressed in liquid form.
- The most widely used absorption refrigeration system is the ammonia-water system, where ammonia serves as the refrigerant and water as the transport medium.
- The work input to the pump is usually very small, and the COP of absorption refrigeration systems is defined as

$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{Q_{gen} + W_{pump,in}} \cong \frac{Q_L}{Q_{gen}}$$



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