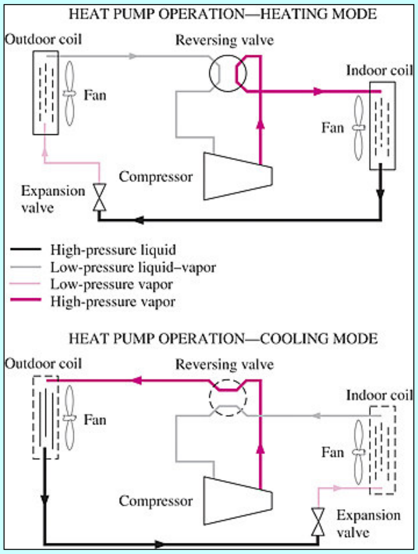
Chapter 10:

Refrigeration Cycles

HEAT PUMP SYSTEMS

- Heat pumps and air conditioners have the same mechanical components.
- Therefore, it is not economical to have two separate systems to meet the heating and cooling requirements of a building.
- One system can be used as a heat pump in winter and an air conditioner in summer.
- This is accomplished by adding a reversing valve to the cycle, as shown.
- As a result of this modification, the condenser of the heat pump (located indoors) functions as the evaporator of the air conditioner in summer.
- Also, the evaporator of the heat pump (located outdoors) serves as the condenser of the air conditioner.



INNOVATIVE VAPOR-COMPRESSION REFRIGERATION SYSTEMS

- The simple vapor-compression refrigeration cycle discussed above is the most widely used refrigeration cycle, and it is adequate for most refrigeration applications.
- The ordinary vapor-compression refrigeration systems are simple, inexpensive, reliable, and practically maintenance-free (when was the last time you serviced your household refrigerator?).
- However, for large industrial applications *efficiency,* not simplicity, is the major concern.
- Also, for some applications the simple vapor-compression refrigeration cycle is inadequate and needs to be modified.
- We now discuss a few such modifications and refinements.

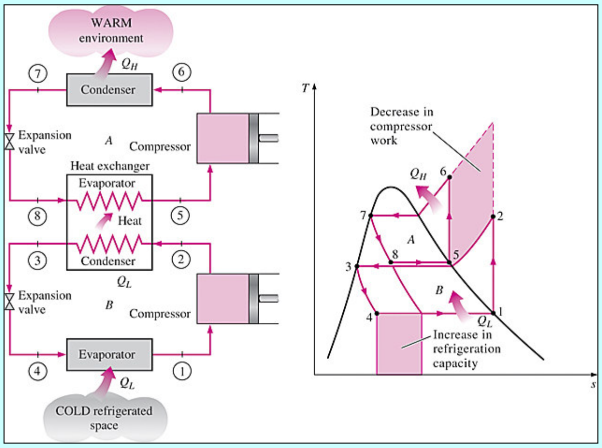
INNOVATIVE VAPOR-COMPRESSION REFRIGERATION SYSTEMS

1. **Cascade Refrigeration Systems**
2. **Multistage Compression Refrigeration Systems**
3. **Multipurpose Refrigeration Systems with a Single Compressor**
4. **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.



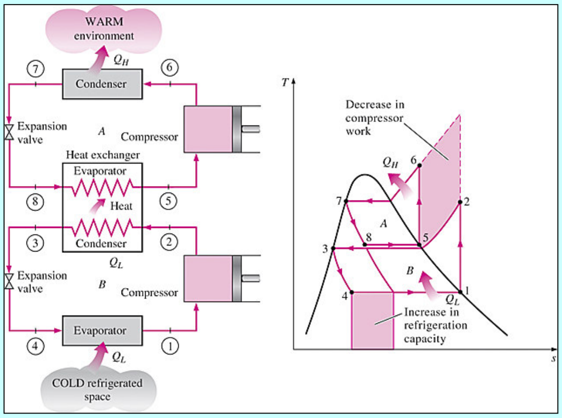
One way of dealing with such situations is to perform the refrigeration process in stages, that is, to have two or more refrigeration cycles that operate in series.

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 (cycle *A*) and the condenser for the bottoming cycle (cycle *B*).



Assuming the heat exchanger is well insulated, 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

$$\frac{\dot{m}_A}{\dot{m}_B} = \frac{(h_2 - h_3)}{(h_5 - h_8)} \qquad COP_{R,cascade} = \frac{\dot{Q}_L}{\dot{W}_{net,in}} = \frac{\dot{m}_B\,(h_1 - h_4)}{\dot{m}_A\,(h_6 - h_5) + \dot{m}_B\,(h_2 - h_1)}$$

Cascade Refrigeration Systems

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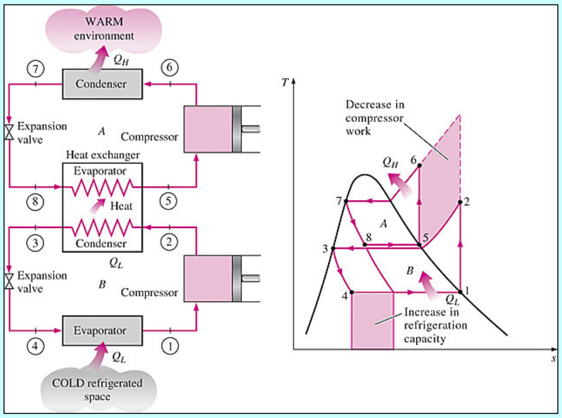
The refrigerants in both cycles are assumed to be the same. This is not necessary.

It is evident from the *T*-*s* diagram that the compressor work decreases and the amount of heat absorbed from the refrigerated space increases.

Therefore, cascading improves the COP of a refrigeration system.

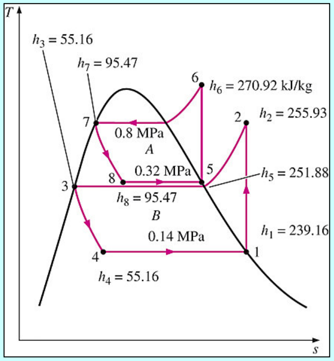


Some refrigeration systems use three or four stages of cascading.

EXAMPLE 10–3

A Two-Stage Cascade Refrigeration Cycle

- 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 counterflow 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 coefficient of performance of this cascade refrigerator.

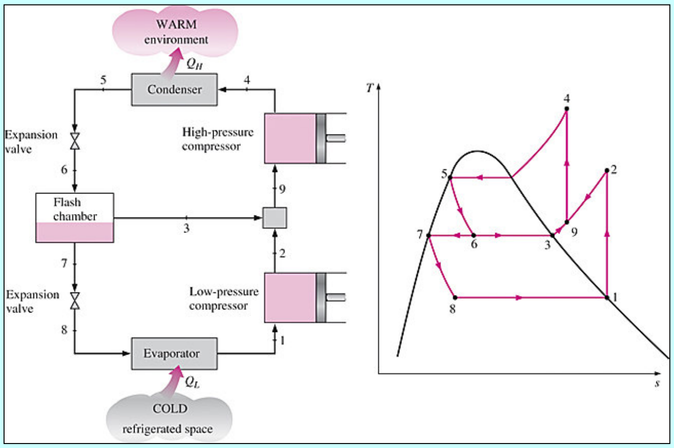


Multistage Compression Refrigeration Systems

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.**

A two stage compression refrigeration system is shown.



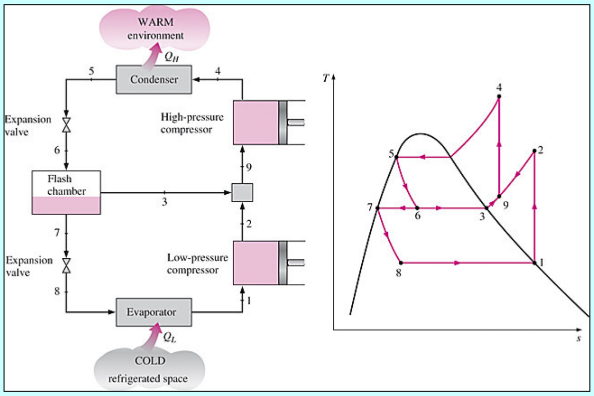
Multistage Compression Refrigeration Systems

In this system, the liquid refrigerant expands in the first expansion valve to the flash chamber pressure, which is the same as the compressor interstage pressure. Part of the liquid vaporizes during this process.

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.

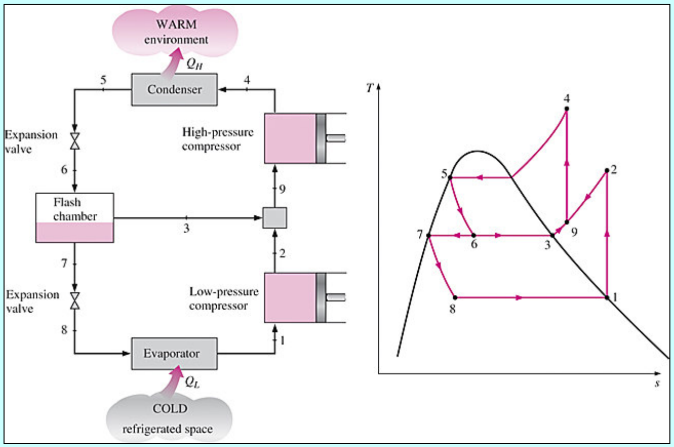
This is, in essence, a regeneration process.

The saturated liquid (state 7) expands through the second expansion valve into the evaporator, where it picks up heat from the refrigerated space.



Multistage Compression Refrigeration Systems

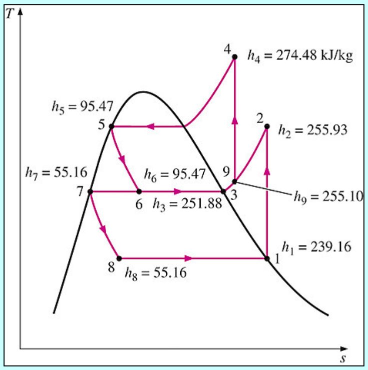
The compression process in this system resembles a two-stage compression with intercooling, and the compressor work decreases. Care should be exercised in the interpretations of the areas on the *T-s* diagram in this case since the mass flow rates are different in different parts of the cycle.



EXAMPLE 10–4

A Two-Stage Refrigeration Cycle with a Flash Chamber

- Consider a two-stage compression refrigeration system operating between the pressure limits of 0.8 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 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.



- Assuming the refrigerant leaves the evaporator as a saturated vapor and both compressors 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 coefficient of performance.

Multipurpose Refrigeration Systems with a Single Compressor

Some applications require refrigeration at more than one temperature.

This could be accomplished by using a separate compressor and a separate throttling valve for each evaporator operating at different temperatures.

However, such a system is bulky and probably uneconomical.

A more practical and economical approach would be to route all the exit streams from the evaporators to a single compressor and let it handle the compression process for the entire system.

Consider, for example, an ordinary refrigerator–freezer unit.

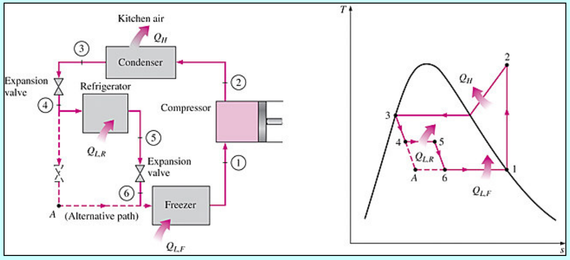
A simplified schematic of the unit and the *T*-*s* diagram of the cycle are shown.

Multipurpose Refrigeration Systems with a Single Compressor

Most refrigerated goods have a high water content, and the refrigerated space must be maintained above the ice point to prevent freezing.

The freezer compartment, however, is maintained at about -18°C. Therefore, the refrigerant should enter the freezer at about -25°C to have heat transfer at a reasonable rate in the freezer.

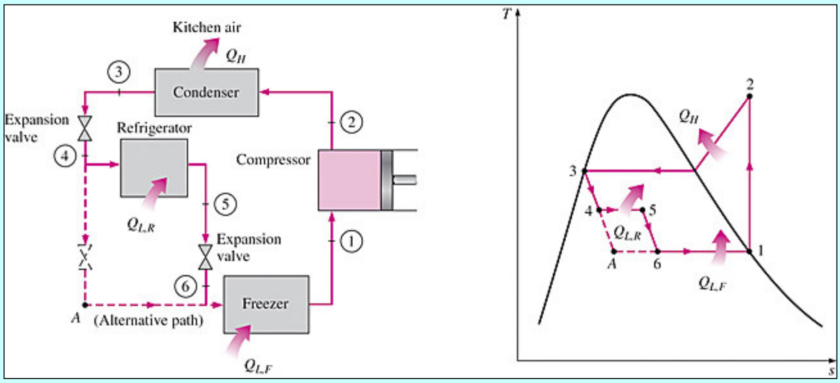
If a single expansion valve and evaporator were used, the refrigerant would have to circulate in both compartments at about -25°C, which would cause ice formation in the neighborhood of the evaporator coils and dehydration of the product.



Multipurpose Refrigeration Systems with a Single Compressor

This problem can be eliminated by throttling the refrigerant to a higher pressure (hence temperature) for use in the refrigerated space and then throttling it to the minimum pressure for use in the freezer.

The entire refrigerant leaving the freezer compartment is subsequently compressed by a single compressor to the condenser pressure.



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.

Some examples of such processes are the separation of oxygen and nitrogen from air, preparation of liquid propellants for rockets, the study of material properties at low temperatures, and the study of some exciting phenomena such as superconductivity.

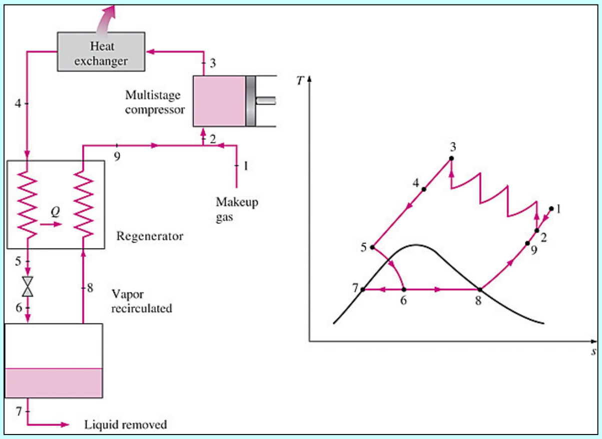
At temperatures above the critical-point value, a substance exists in the gas phase only. The critical temperatures of helium, hydrogen, and nitrogen (three commonly used liquefied gases) are -268, -240, and -147°C, respectively.

Therefore, none of these substances exist in liquid form at atmospheric conditions. Furthermore, low temperatures of this magnitude cannot be obtained by ordinary refrigeration techniques. Then the question is : *How can we lower the temperature of a gas below its critical-point value?*

Liquefaction of Gases

Several cycles, some complex and others simple, are used successfully for the liquefaction of gases. Below we discuss the Linde-Hampson cycle, which is shown schematically and on a *T-s* diagram in Fig. 11–15.

Makeup gas is mixed with the uncondensed portion of the gas from the previous cycle, and the mixture at state 2 is compressed by a multistage compressor to state 3.



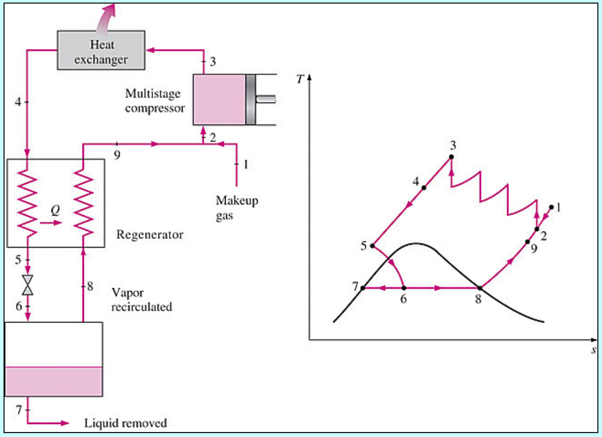
The compression process approaches an isothermal process due to intercooling.

The high-pressure gas is cooled in an aftercooler by a cooling medium or by a separate external refrigeration system to state 4.

Liquefaction of Gases

The gas is further cooled in a regenerative counter-flow heat exchanger by the uncondensed portion of gas from the previous cycle to State 5, and it is throttled to state 6, which is a saturated liquid–vapor mixture state.

The liquid (state 7) is collected as the desired product, and the vapor (state 8) is routed through the regenerator to cool the high-pressure gas approaching the throttling valve.

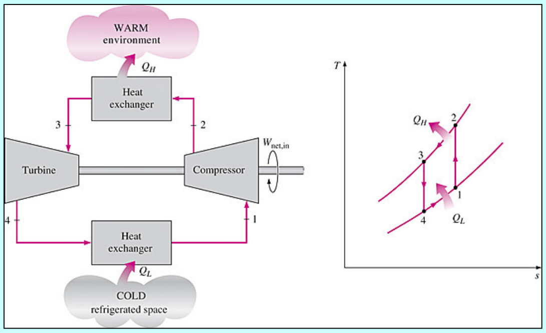


Finally, the gas is mixed with fresh makeup gas, and the cycle is repeated.

This and other refrigeration cycles used for the liquefaction of gases can also be used for the solidification of gases.

GAS REFRIGERATION CYCLES

The vapor-compression refrigeration cycle is essentially a modified Rankine cycle operating in reverse.
In this section, we discuss the *reversed Brayton cycle,* better known as the **gas refrigeration cycle.**



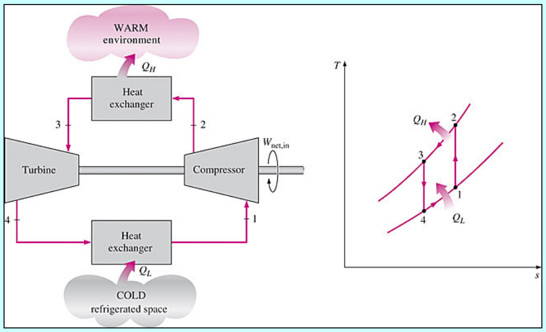
Consider the gas refrigeration cycle shown. The surroundings are at T_0, and the refrigerated space is to be maintained at T_L. The gas is compressed during process 1-2. The high-pressure, high-temperature gas at state 2 is then cooled at constant pressure to T_0 by rejecting heat to the surroundings.

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.

GAS REFRIGERATION CYCLES

All the processes described are internally reversible, and the cycle executed is the *ideal* gas refrigeration cycle. In actual gas refrigeration cycles, the compression and expansion processes deviate from the isentropic ones, and T_3 is higher than T_0 unless the heat exchanger is infinitely large.

On a *T*-*s* diagram, the area under process curve 4-1 represents the heat removed from the refrigerated space, and the enclosed area 1-2-3-4-1 represents the net work input. The ratio of these areas is the COP for the cycle, which may be expressed as:



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

where

$$q_L = h_1 - h_4$$

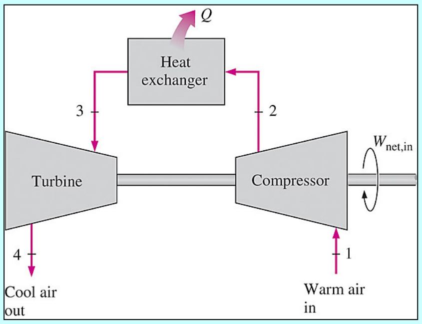
$$w_{turb,out} = h_3 - h_4$$

$$w_{comp,in} = h_2 - h_1$$

GAS REFRIGERATION CYCLES

The gas refrigeration cycle deviates from the reversed Carnot cycle because the heat transfer processes are not isothermal. In fact, the gas temperature varies considerably during heat transfer processes. Consequently, the gas refrigeration cycles have lower COPs relative to the vapor-compression refrigeration cycles or the reversed Carnot cycle.

Despite their relatively low COPs, the gas refrigeration cycles have two desirable characteristics: They involve simple, lighter components, which make them suitable for aircraft cooling, and they can incorporate regeneration, which makes them suitable for liquefaction of gases and cryogenic applications.

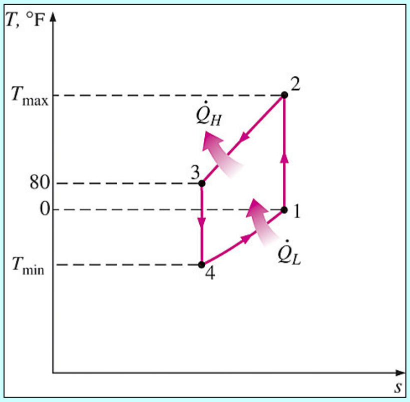


An open-cycle aircraft cooling system is shown. Atmospheric air is compressed by a compressor, cooled by the surrounding air, and expanded in a turbine. The cool air leaving the turbine is then directly routed to the cabin.

EXAMPLE 10–5

The Simple Ideal Gas Refrigeration Cycle

- An ideal gas refrigeration cycle using air as the working medium is to maintain a refrigerated space at 0°F while rejecting heat to the surrounding medium at 80°F. The pressure ratio of the compressor is 4. Determine:
- (*a*) the maximum and minimum temperatures in the cycle,
- (*b*) the coefficient of performance, and
- (*c*) the rate of refrigeration for a mass flow rate of 0.1 lbm/s.



ABSORPTION REFRIGERATION SYSTEMS

Another form of refrigeration that becomes economically attractive when there is a source of inexpensive thermal energy at a temperature of 100 to 200°C is **absorption refrigeration.** Some examples of inexpensive thermal energy sources are geothermal energy and solar energy etc.

As the name implies, absorption refrigeration systems involve the absorption of a *refrigerant* by a *transport medium*.

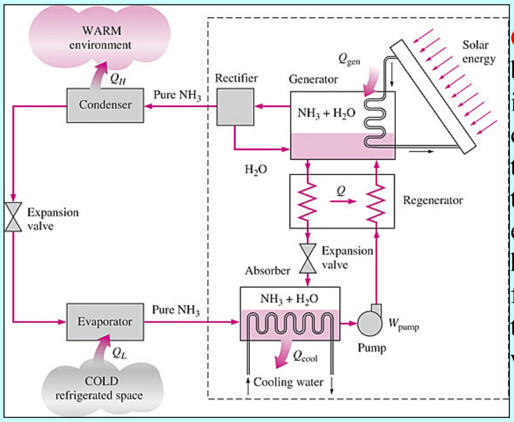
The most widely used absorption refrigeration system is the ammonia–water system, where ammonia (NH_3) serves as the refrigerant and water (H_2O) as the transport medium.

Other absorption refrigeration systems include water–lithium bromide and water–lithium chloride systems, where water serves as the refrigerant.

The latter two systems are limited to applications such as air-conditioning where the minimum temperature is above the freezing point of water.

ABSORPTION REFRIGERATION SYSTEMS

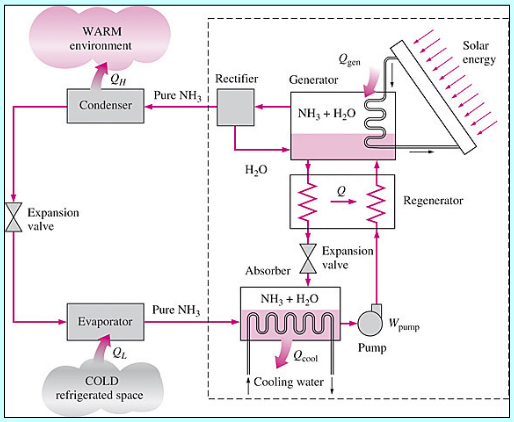
To understand the basic principles involved in absorption refrigeration, we examine the NH_3-H_2O system shown. You will immediately notice from the figure that this system looks very much like the vapor-compression system, except that the compressor has been replaced by a complex absorption mechanism consisting of an absorber, a pump, a generator, a regenerator, a valve, and a rectifier.



Once the pressure of NH_3 is raised by the components in the box (this is the only thing they are set up to do), it is cooled and condensed in the condenser by rejecting heat to the surroundings, is throttled to the evaporator pressure, and absorbs heat from the refrigerated space as it flows through the evaporator. So, there is nothing new there. Here is what happens in the box:

ABSORPTION REFRIGERATION SYSTEMS

Ammonia vapor leaves the evaporator and enters the absorber, where it dissolves and reacts with water to form NH_3-H_2O. This is an exothermic reaction; thus heat is released during this process. The amount of NH_3 that can be dissolved in H_2O is inversely proportional to the temperature. Therefore, it is necessary to cool the absorber to maintain its temperature as low as possible, hence to maximize the amount of NH_3 dissolved in water. The liquid NH_3-H_2O solution, which is rich in NH3, is then pumped to the generator.

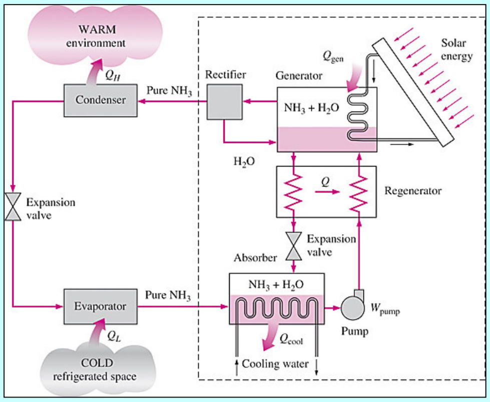


Heat is transferred to the solution from a source to vaporize some of the solution. The vapor, which is rich in NH_3, passes through a rectifier, which separates the water and returns it to the generator. The high-pressure pure NH3 vapor then continues its journey through the rest of the cycle. The hot NH_3-H_2O solution, which is weak in NH_3, then passes through a regenerator, where it transfers some heat to the rich solution leaving the pump, and is throttled to the absorber pressure.

ABSORPTION REFRIGERATION SYSTEMS

Compared with vapor-compression systems, absorption refrigeration systems have one major advantage:

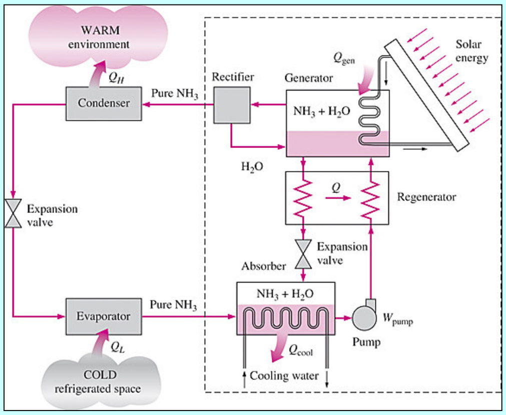
A liquid is compressed instead of a vapor. The steady-flow work is proportional to the specific volume, and thus the work input for absorption refrigeration systems is very small (on the order of one percent of the heat supplied to the generator) and often neglected in the cycle analysis.



The operation of these systems is based on heat transfer from an external source. Therefore, absorption refrigeration systems are often classified as *heat-driven systems*.

ABSORPTION REFRIGERATION SYSTEMS

The absorption refrigeration systems 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, absorption refrigeration systems should be considered only when the unit cost of thermal energy is low and is projected to remain low relative to electricity.



Absorption refrigeration systems are primarily used in large commercial and industrial installations.

The COP of absorption refrigeration systems is defined as

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