Chapter 6

The objectives of this Chapter are to:

- Introduce the concepts of refrigerators and heat pumps and the measure of their performance.
- Analyze the ideal vapor-compression refrigeration cycle.
- Analyze the actual vapor-compression refrigeration cycle.
- Review the factors involved in selecting the right refrigerant for an application.
- Discuss the operation of refrigeration and heat pump systems.
- Evaluate the performance of innovative vapor-compression refrigeration systems.
- Analyze gas refrigeration systems.
- Introduce the concepts of absorption-refrigeration systems.

6.1: Introduction to Refrigerators and Heat Pumps

- A major application area of thermodynamics is ***refrigeration***, which is the transfer of heat from a **lower temperature region** to a **higher temperature region**.
- Devices that produce refrigeration are called ***refrigerators***, and the cycles on which they operate are called ***refrigeration cycles***.
- The most frequently used refrigeration cycle is the ***vapor-compression refrigeration cycle*** in which the refrigerant is **vaporized** and **condensed alternately** and is compressed in the vapor phase. which involves **four** main components:
  - ✓ a compressor,
  - ✓ a condenser,
  - ✓ an expansion valve, and
  - ✓ an evaporator, as shown in Fig. 6.1.

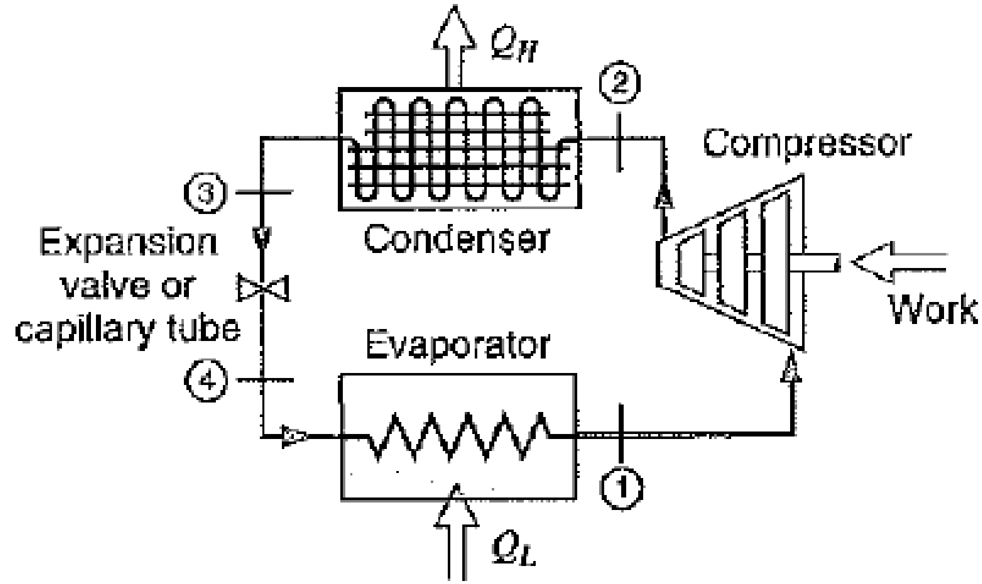

FIGURE 6.1: Basic components of the ideal vapor compression refrigeration cycle

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- Another well-known refrigeration cycle is the ***gas refrigeration cycle*** in which the refrigerant remains in the **gaseous phase throughout**.
- Other refrigeration cycles discussed in this chapter are ***cascade refrigeration***, where more than one refrigeration cycle is used; *absorption refrigeration*, where the refrigerant is dissolved in a liquid before it is compressed; and, as a Topic of Special Interest, *thermoelectric refrigeration*, where refrigeration is produced by the passage of electric current through two dissimilar materials.

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- We all know from experience that heat flows in the direction of **decreasing temperature**, that is, from high-temperature regions to low-temperature ones.
  - ✓ This heat-transfer process occurs in nature without requiring any devices.
- The reverse process, however, cannot occur by itself. The transfer of heat from a **low-temperature region** to a **high-temperatur**e one requires special devices called **refrigerators.**
- Refrigerators are cyclic devices, and the working fluids used in the refrigeration cycles are called **refrigerants.** A refrigerator is shown schematically in Fig. 6.2*a*.

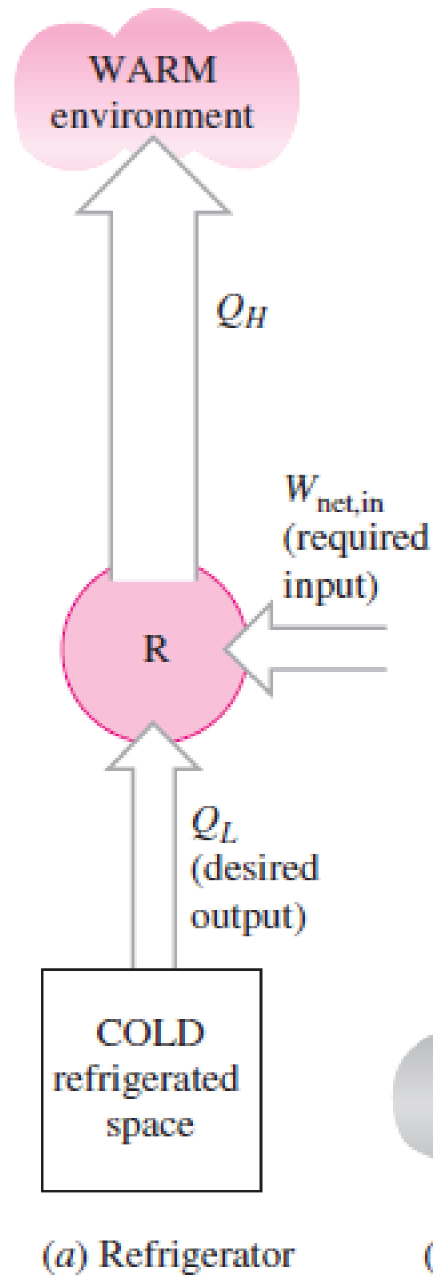

FIGURE 6.2: The objective of a refrigerator is to remove heat (Q_L) from the cold medium

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- Here Q_L is the magnitude of the heat removed from the refrigerated space at temperature T_L , Q_H is the magnitude of the heat rejected to the warm space at temperature T_H , and $W_{net,in}$ is the net work input to the refrigerator. Since Q_L and Q_H represent magnitudes and thus are positive quantities.
- Another device that transfers heat from a **low-temperature medium** to a **high-temperature** one is the **heat pump.**
- 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 from it. Discharging this heat to a higher-temperature medium is merely a necessary part of the operation, not the purpose.
  - ✓ The objective of a heat pump, however, is to maintain a heated space at a high temperature. This is accomplished by absorbing heat from a low-temperature source, such as well water or cold outside air in winter, and supplying this heat to a warmer medium such as a house (Fig. 6.2*b*).

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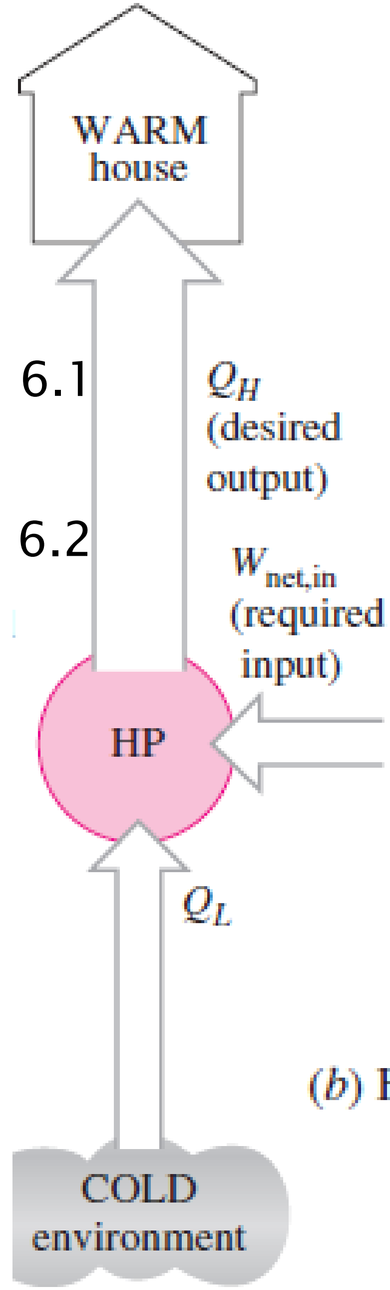
- The performance of refrigerators and heat pumps is expressed in terms of the **coefficient of performance** (COP), defined as

$$COP_R = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{net,in}} \quad \text{........ 6.1}$$

$$COP_{HP} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{net,in}} \quad \text{........ 6.2}$$

✓ These relations can also be expressed in the rate form by replacing the quantities Q_L, Q_H, and $W_{net,in}$ by $\dot{Q}_L$, $\dot{Q}_H$, and $\dot{W}_{net,in}$, respectively. Notice that both COP_R and COP_{HP} can be **greater than 1**. A comparison of Eqs. 6.1 and 6.2 reveals that

$$COP_{HP} = COP_R + 1 \quad \text{.................. 6.3}$$



(b) Heat pump

FIGURE 6.2: The objective of a heat pump is to supply heat (Q_H) to a warm medium.

The Reversed Carnot Cycle

- Recall that the Carnot cycle is a totally reversible cycle that consists of two reversible isothermal and two isentropic processes. It has the maximum thermal efficiency for given temperature limits, and it serves as a standard against which actual power cycles can be compared.
  - ✓ Since it is a reversible cycle, all four processes that comprise the Carnot cycle can be reversed.
  - ✓ Reversing the cycle does also reverse the directions of any heat and work interactions. The result is a cycle that operates in the counterclockwise direction on a *T-s* diagram, which is called 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.**
- Consider a reversed Carnot cycle executed within the saturation dome of a refrigerant, as shown in Fig. 6.3

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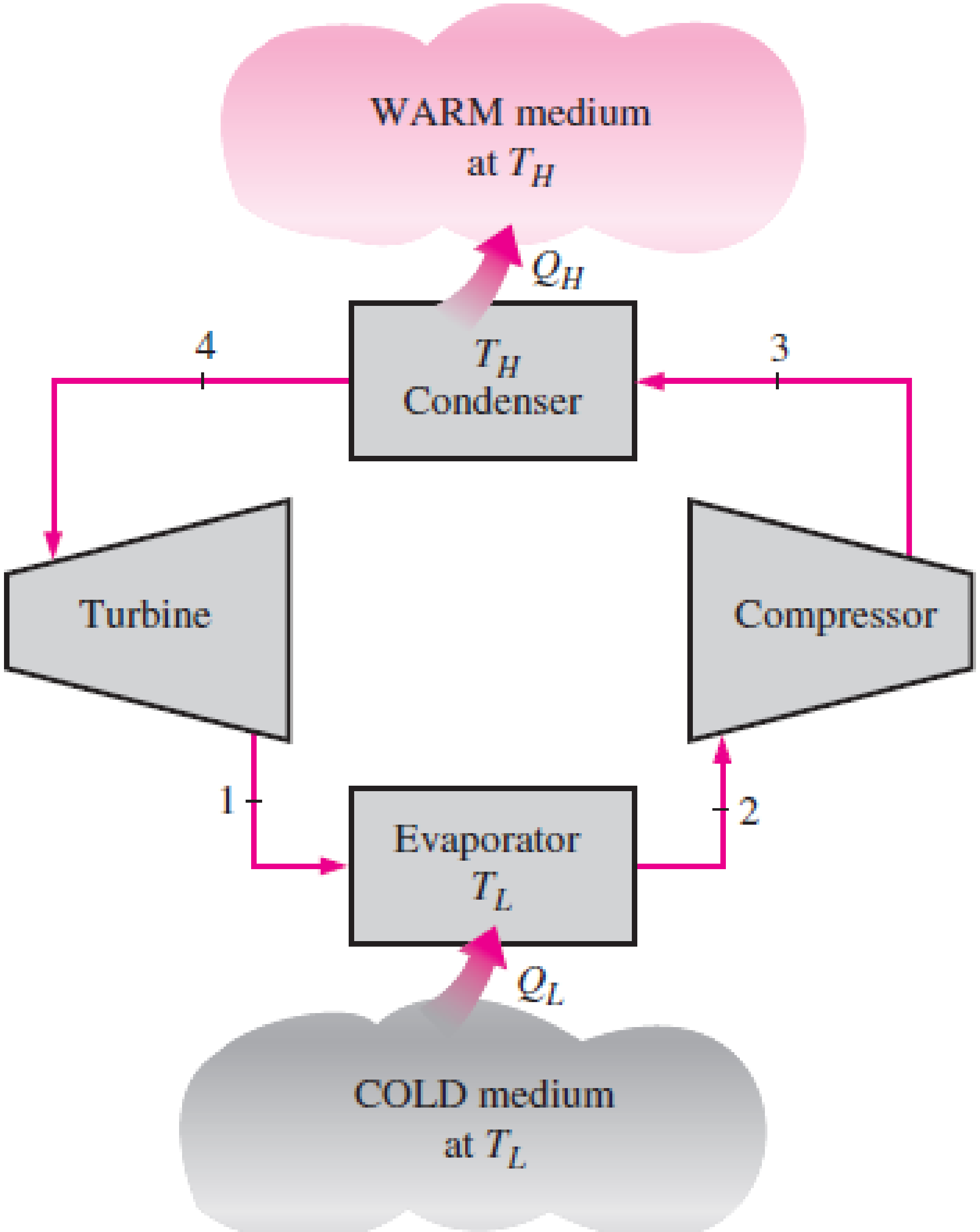
- The refrigerant absorbs heat isothermally from a low-temperature source at T_L in the amount of Q_L (process 1-2), is compressed isentropically to state 3 (temperature rises to T_H), rejects heat isothermally to a high-temperature sink at T_H in the amount of Q_H (process 3-4), and expands isentropically to state 1 (temperature drops to T_L). The refrigerant changes from a saturated vapor state to a saturated liquid state in the condenser during process 3-4.
- The coefficients of performance of Carnot refrigerators and heat pumps are expressed in terms of temperatures as

$$\text{COP}_{\text{R,Carnot}} = \frac{1}{T_H/T_L - 1} \quad \text{.................. 6.4}$$

$$\text{COP}_{\text{HP,Carnot}} = \frac{1}{1 - T_L/T_H} \quad \text{.............. 6}$$

- Notice that both COPs increase as the difference between the two temperatures decreases, that is, as T_L rises or T_H falls.
- The reversed Carnot cycle is the *most efficient* refrigeration cycle operating between two specified temperature levels. Therefore, it is natural to look at it first as a prospective ideal cycle for refrigerators and heat pumps. If we could, we certainly would adapt it as the ideal cycle. As explained below, however, the reversed Carnot cycle is **not a suitable model for refrigeration cycles**



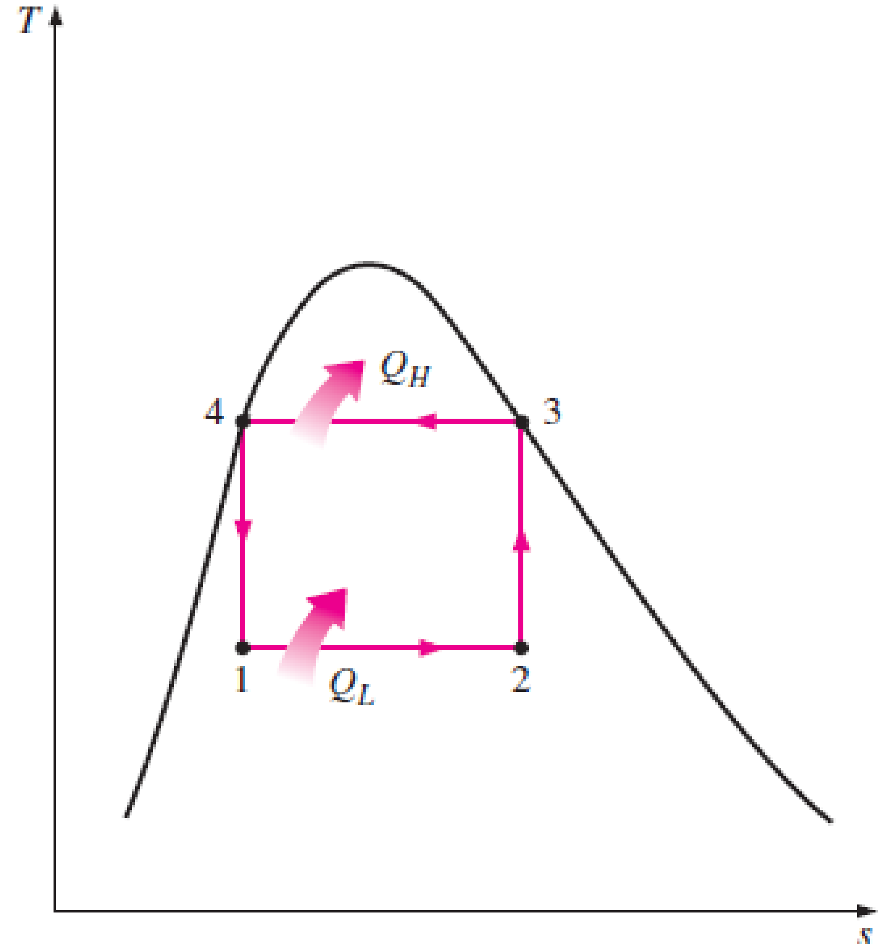


FIGURE 6.3: Schematic of a Carnot refrigerator and *T*-*s* diagram of the reversed Carnot cycle

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- The two isothermal heat transfer processes are not difficult to achieve in practice since maintaining a constant pressure automatically fixes the temperature of a two-phase mixture at the saturation value. Therefore, processes 1-2 and 3-4 can be approached closely in actual evaporators and condensers.
- However, processes 2-3 and 4-1 cannot be approximated closely in practice. This is because process 2-3 involves the compression of a liquid–vapor mixture, which requires a compressor that will handle two phases, and process 4-1 involves the expansion of high-moisture-content refrigerant in a turbine. It seems as if these problems could be eliminated by executing the reversed Carnot cycle outside the saturation region. But in this case we have difficulty in maintaining isothermal conditions during the heat-absorption and heat-rejection processes. Therefore, we conclude that the reversed Carnot cycle cannot be approximated in actual devices and is not a realistic model for refrigeration cycles. However, the reversed Carnot cycle can serve as a standard against which actual refrigeration cycles are compared.

The Ideal Vapor-compression Refrigeration Cycle

- Many of the impracticalities associated with the **reversed Carnot cycle** can be eliminated by **vaporizing the refrigerant completely** before it is compressed and by **replacing the turbine with a throttling device**, such as an **expansion valve or capillary tube**. The cycle that results is called the **ideal vapor-compression refrigeration cycle,** and it is shown schematically and on a *T-s* diagram in **Fig. 6.4**.
- The **vapor-compression refrigeration cycle** is the most widely used cycle for **refrigerators**, **air-conditioning systems**, and **heat pumps**. It consists of four processes:

Process	1-2	Isentropic compression in a compressor
Process	2-3	Constant-pressure heat rejection in a condenser
Process	3-4	Throttling in an expansion device
Process	4-1	Constant-pressure heat absorption in an evaporator

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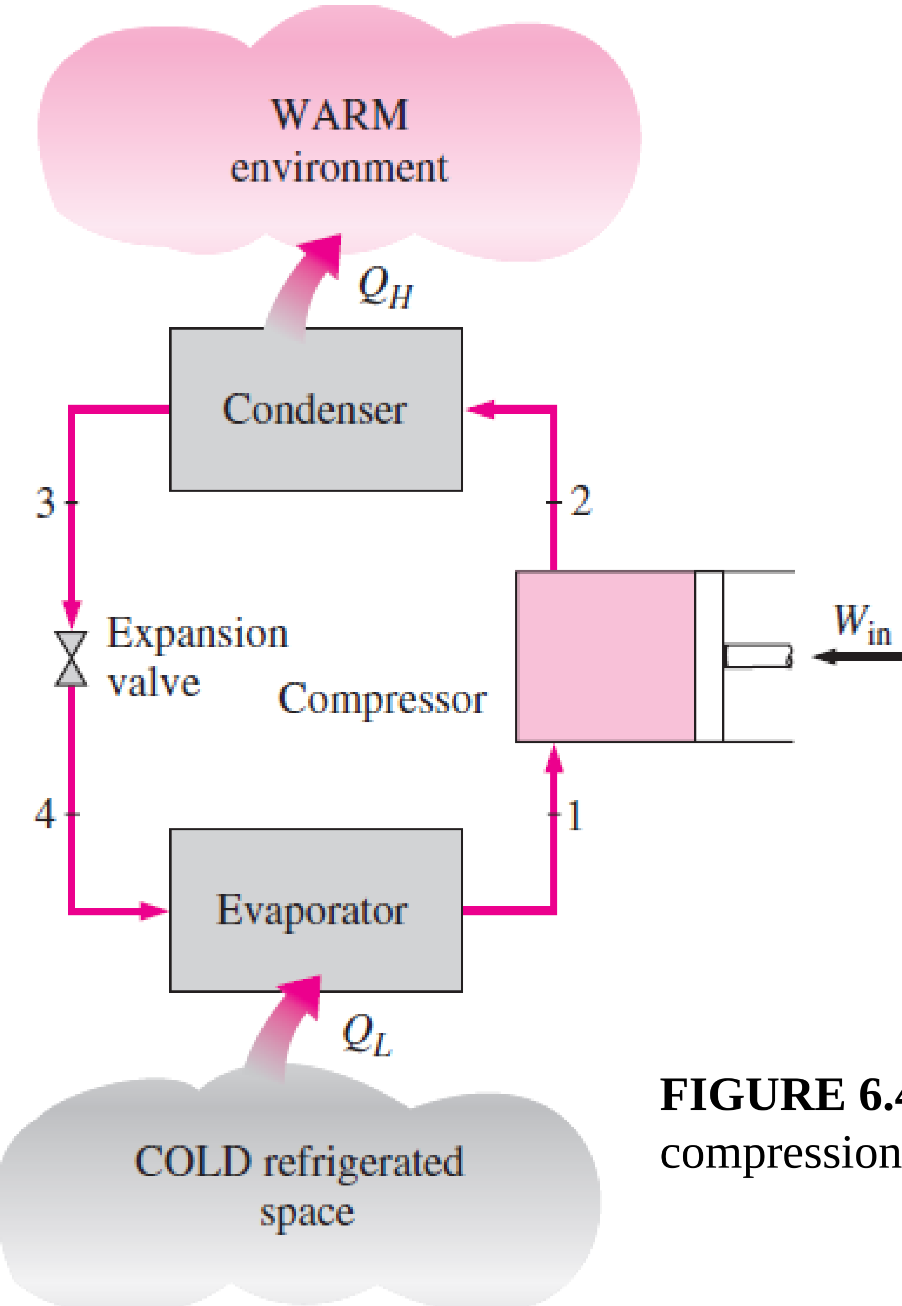

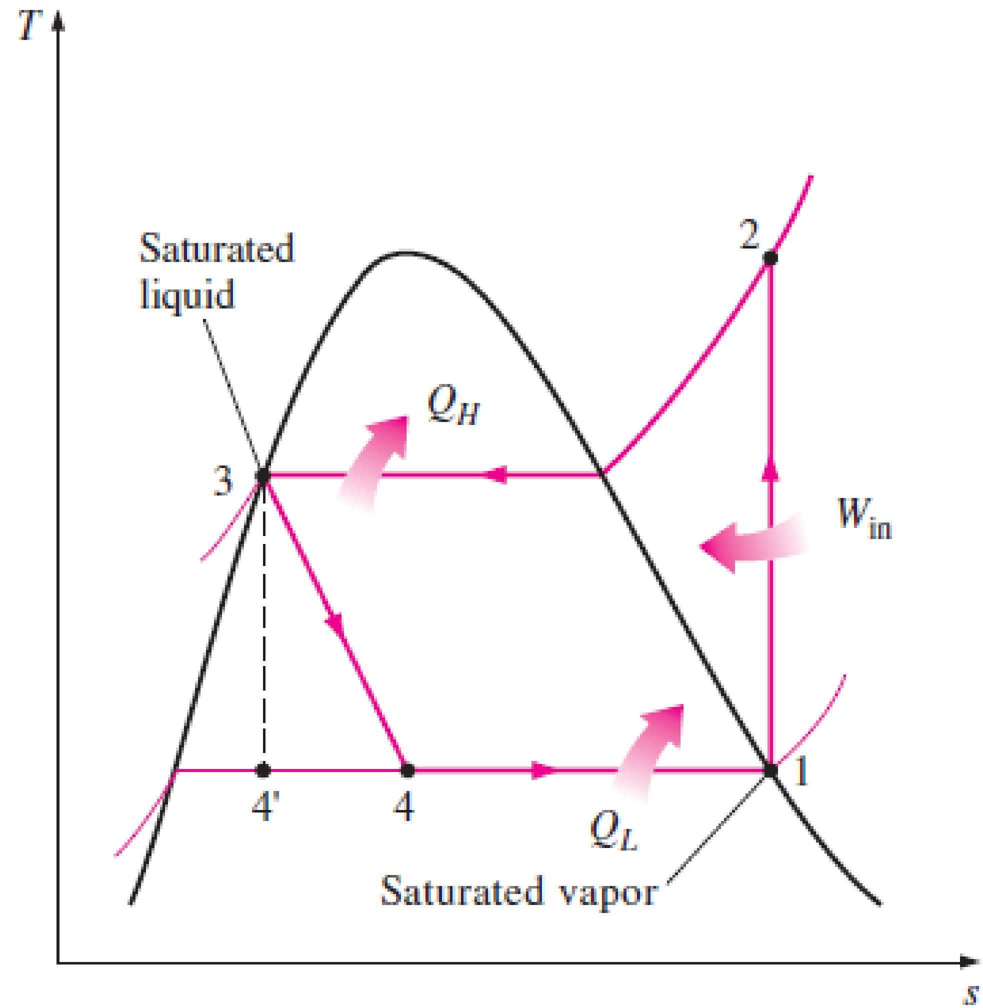

FIGURE 6.4: Schematic and *T*-*s* diagram for the ideal vapor-compression refrigeration cycle

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- In an 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 superheated vapor at state 2 and leaves as saturated liquid at state 3 as a result of heat rejection to the surroundings. The temperature of the refrigerant at this state is still above the temperature of the surroundings.
- The saturated liquid refrigerant at state 3 is throttled to the evaporator pressure by passing it through an expansion valve or capillary tube. The temperature of the refrigerant drops below the temperature of the refrigerated space during this process. The refrigerant enters the evaporator at state 4 as a low-quality saturated mixture, and it completely evaporates by absorbing heat from the refrigerated space. The refrigerant leaves the evaporator as saturated vapor and reenters the compressor, completing the cycle.

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- All **four components** associated with the vapor-compression refrigeration cycle are steady-flow devices, and thus all four processes that make up the cycle can be analyzed as steady-flow processes. The kinetic and potential energy changes of the refrigerant are usually small relative to the work and heat transfer terms, and therefore they can be neglected. Then the steady flow energy equation on a unit–mass basis reduces to

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

- The condenser and the evaporator do not involve any work, and the compressor can be approximated as adiabatic. Then the COPs of refrigerators and heat pumps operating on the vapor-compression refrigeration cycle can be expressed as

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

and

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

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

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EXAMPLE 1: The Ideal Vapor-Compression Refrigeration Cycle

- 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, and (*c*) the COP of the refrigerator.

Actual Vapor-Compression Refrigeration Cycle

- An actual vapor-compression refrigeration cycle differs from the ideal one in several ways, owing mostly to the **irreversibilities** that occur in various components.
- Two common sources of irreversibilities are **fluid friction** (causes pressure drops) and **heat transfer** to or from the surroundings. The *T-s* diagram of an actual vapor-compression refrigeration cycle is shown in Fig. 6.5

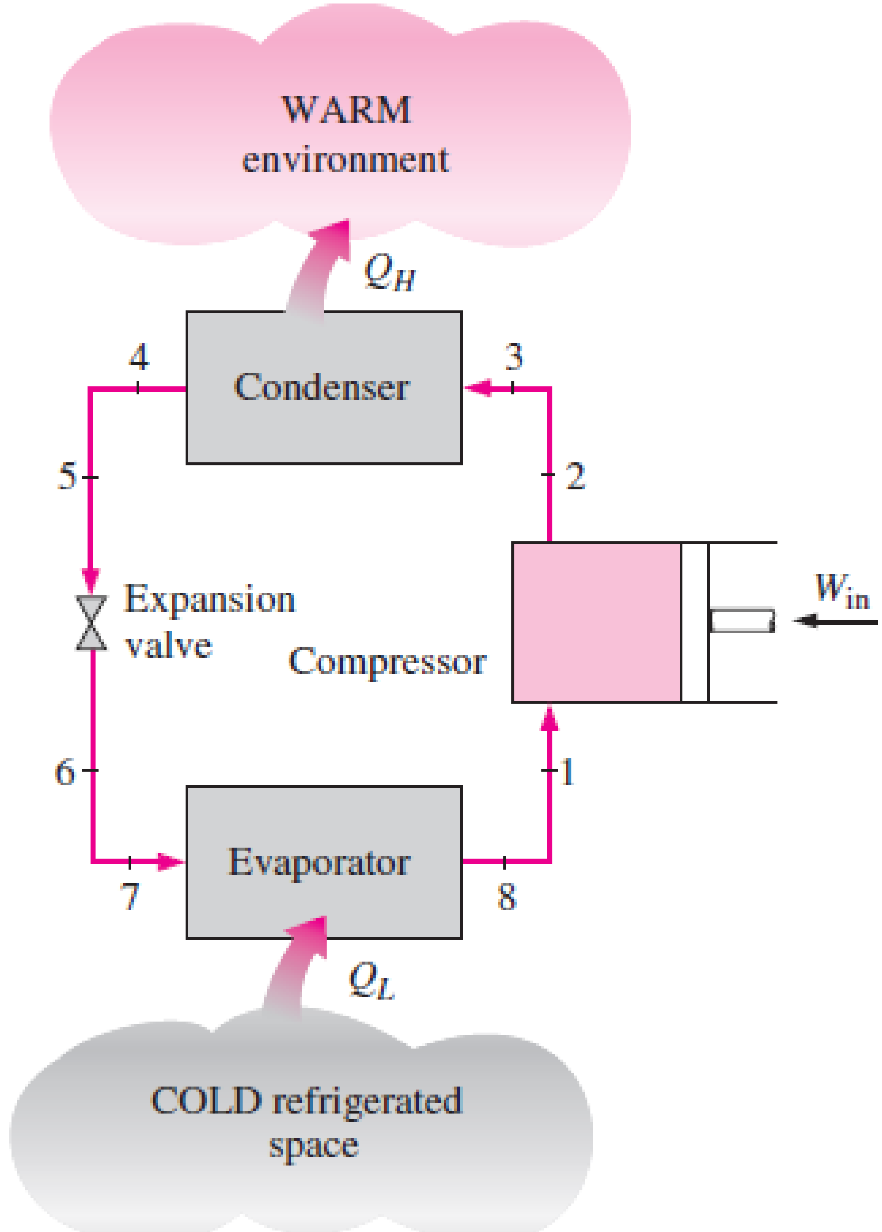
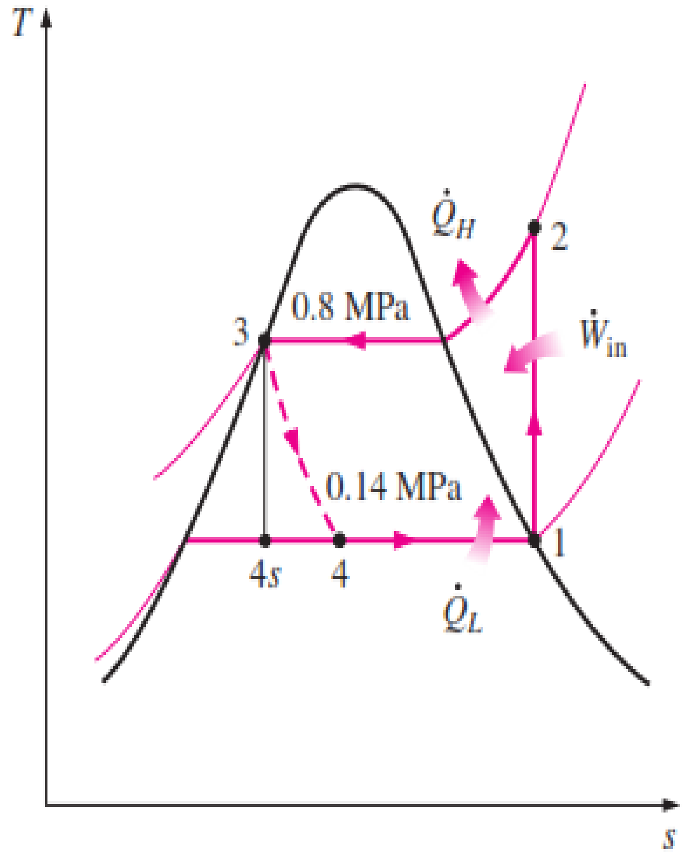


Fig. 6.5



$$P_1 = 0.14\ \text{MPa} \longrightarrow h_1 = h_{g\,@\,0.14\ \text{MPa}} = 239.16\ \text{kJ/kg}$$

$$s_1 = s_{g\,@\,0.14\ \text{MPa}} = 0.94456\ \text{kJ/kg}\cdot\text{K}$$

$$\left.\begin{array}{l} P_2 = 0.8\ \text{MPa} \\ s_2 = s_1 \end{array}\right\} h_2 = 275.39\ \text{kJ/kg}$$

$$P_3 = 0.8\ \text{MPa} \longrightarrow h_3 = h_{f\,@\,0.8\ \text{MPa}} = 95.47\ \text{kJ/kg}$$

$$h_4 \cong h_3\ (\text{throttling}) \longrightarrow h_4 = 95.47\ \text{kJ/kg}$$

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(*a*) The rate of heat removal from the refrigerated space and the power input to the compressor are determined from their definitions:

$$\dot{Q}_L = \dot{m}(h_1 - h_4) = (0.05 \text{ kg/s})[(239.16 - 95.47) \text{ kJ/kg}] = \mathbf{7.18 \text{ kW}}$$

and

$$\dot{W}_{\text{in}} = \dot{m}(h_2 - h_1) = (0.05 \text{ kg/s})[(275.39 - 239.16) \text{ kJ/kg}] = \mathbf{1.81 \text{ kW}}$$

(*b*) The rate of heat rejection from the refrigerant to the environment is

$$\dot{Q}_H = \dot{m}(h_2 - h_3) = (0.05 \text{ kg/s})[(275.39 - 95.47) \text{ kJ/kg}] = \mathbf{9.0 \text{ kW}}$$

It could also be determined from

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

(*c*) The coefficient of performance of the refrigerator is

$$\text{COP}_\text{R} = \frac{\dot{Q}_L}{\dot{W}_{\text{in}}} = \frac{7.18 \text{ kW}}{1.81 \text{ kW}} = \mathbf{3.97}$$

Selecting the Right Refrigerant

- When designing a **refrigeration system**, there are **several refrigerants** from which to choose, 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).
- **Selection of refrigerant** for a particular application is based on the following requirements:
  - ✓ Thermodynamic and thermo-physical properties
  - ✓ Environmental and safety properties (less toxics) , and
  - ✓ Economical aspects

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- The right choice of refrigerant depends on the **situation at hand**. Of these, refrigerants such as **R-11**, **R-12**, **R-22**, **R-134a**, and **R-502** account for over **90 percent** of the market in the **United States**.
- *Ethyl ether* was the first commercially used refrigerant in vapor-compression systems in 1850, followed by ammonia, carbon dioxide, methyl chloride, sulphur dioxide, butane, ethane, propane, isobutane, gasoline, and chlorofluorocarbons, among others.
- The industrial and heavy-commercial sectors were very satisfied with ***ammonia***, and still are, although **ammonia is toxic**.
- The advantages of ammonia over other refrigerants are its **low cost**, **higher COPs** (and thus lower energy cost), **more favorable thermodynamic** and **transport properties** and thus **higher heat transfer coefficients** (requires smaller and lower-cost heat exchangers), **greater detectability** in the event of a leak, and **no effect on the ozone layer**.
- The major **drawback of ammonia** is its **toxicity**, which makes it unsuitable for domestic use.
- Ammonia is predominantly used in food refrigeration facilities such as the cooling of fresh fruits, vegetables, meat, and fish; refrigeration of beverages and dairy products such as beer, wine, milk, and cheese; freezing of ice cream and other foods; ice production; and low-temperature refrigeration in the pharmaceutical and other process industries.

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- It is remarkable that the early refrigerants used in the light-commercial and household sectors such as **sulfur dioxide**, **ethyl chloride**, and **methyl chloride** were **highly toxic**. The widespread publicity of a few instances of leaks that resulted in serious illnesses and death in the 1920s caused a public cry to **ban or limit** the use of these refrigerants, creating a need for the development of a safe refrigerant for household use.
- The versatility, low cost, being nontoxic, noncorrosive, nonflammable, and chemically stable; having a high enthalpy of vaporization (minimizes the mass flow rate); and, of course, being available at low cost, friendly to the ozone layer or less greenhouse effect, the temperatures of the two media (the refrigerated space and the environment) with which the refrigerant exchanges heat (i.e., To have heat transfer at a reasonable rate, a temperature difference of 5 to 10°C should be maintained between the refrigerant and the medium with which it is exchanging heat. If a refrigerated space is to be maintained at -10°C, for example, the temperature of the refrigerant should remain at about -20°C while it absorbs heat in the evaporator.), made them the refrigerants of choice.