Thermodynamics and Heat Transfer Chapter 11: Refrigeration Cycles

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Learning Outcomes:

- 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.
- Heat Pump
- Innovative vapor-compression refrigeration systems.
- Absorption-refrigeration system

Video Credit: https://youtu.be/gVLhrLTF878

Refrigeration and Heat Pump

Heat flows in the direction of decreasing temperature, that is, from high-temperature regions to low-temperature ones.

The reverse process, however, cannot occur by itself. The transfer of heat from a low-temperature region to a high-temperature one requires special devices called refrigerators.

Here QL is the magnitude of the heat removed from the refrigerated space at temperature TL

QH is the magnitude of the heat rejected to the warm space at temperature TH

Wnet,in is the net work input to the refrigerator

$$\mathrm{COP_R} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Cooling effect}}{\text{Work input}} = \frac{Q_L}{W_{\text{net,in}}} \qquad \textbf{(11–1)}$$

$$\mathrm{COP_{HP}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating effect}}{\text{Work input}} = \frac{Q_H}{W_{\text{net,in}}} \qquad \textbf{(11–2)}$$

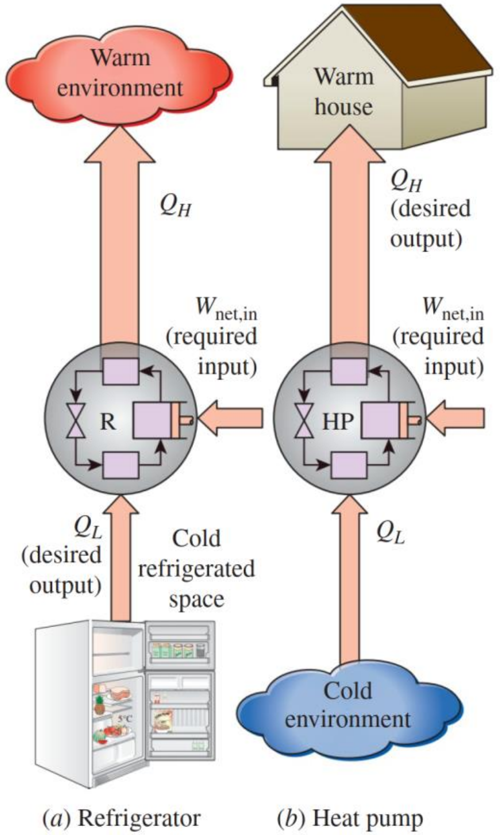
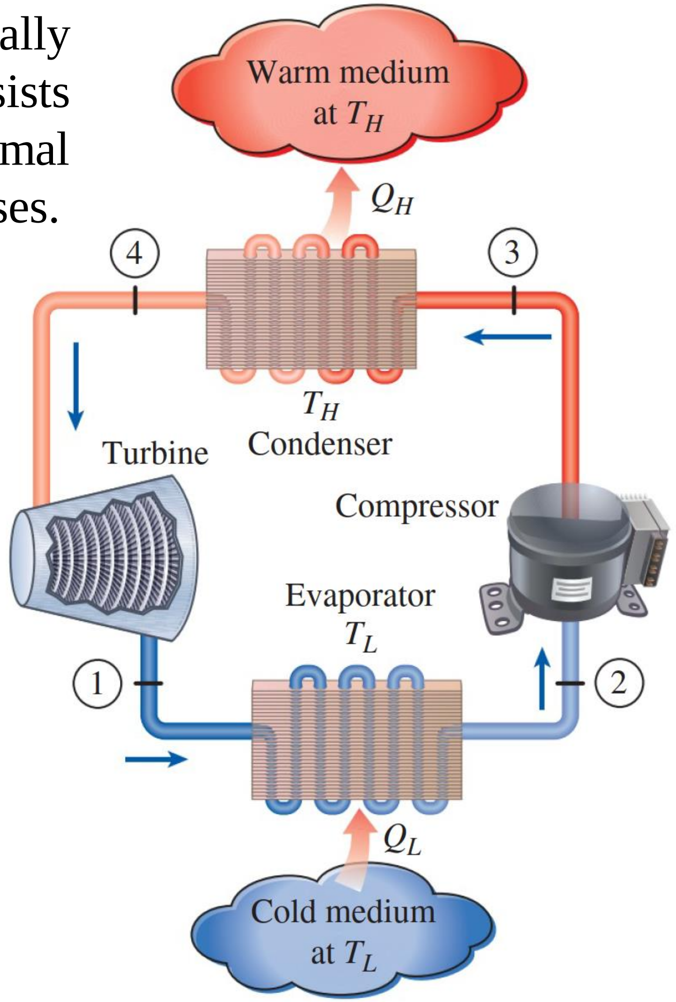


FIGURE 11–1
The objective of a refrigerator is to remove heat (Q_L) from the cold medium; the objective of a heat pump is to supply heat (Q_H) to a warm medium.

THE REVERSED CARNOT CYCLE

Carnot cycle is a totally reversible cycle that consists of two reversible isothermal and two isentropic processes.



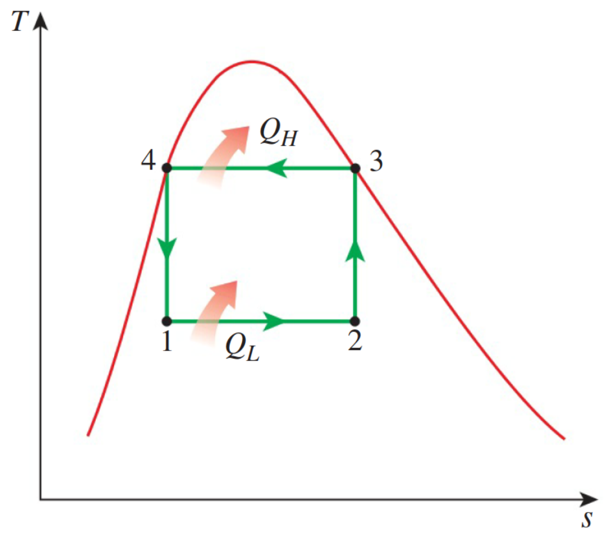


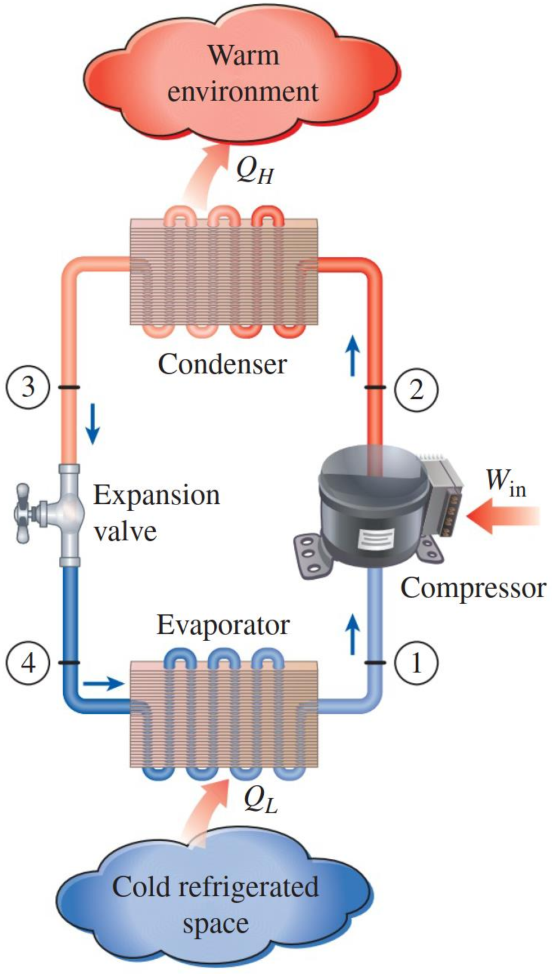
FIGURE 11–2
Schematic of a Carnot refrigerator and T-s diagram of the reversed Carnot cycle.

$$\mathrm{COP}_{\mathrm{R,Carnot}} = \frac{1}{T_H/T_L - 1} \quad (11\text{–}4)$$

$$\mathrm{COP}_{\mathrm{HP,Carnot}} = \frac{1}{1 - T_L/T_H} \quad (11\text{–}5)$$

It has the maximum thermal efficiency for given temperature limits, and it serves as a standard against which actual power cycles can be compared.

THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE



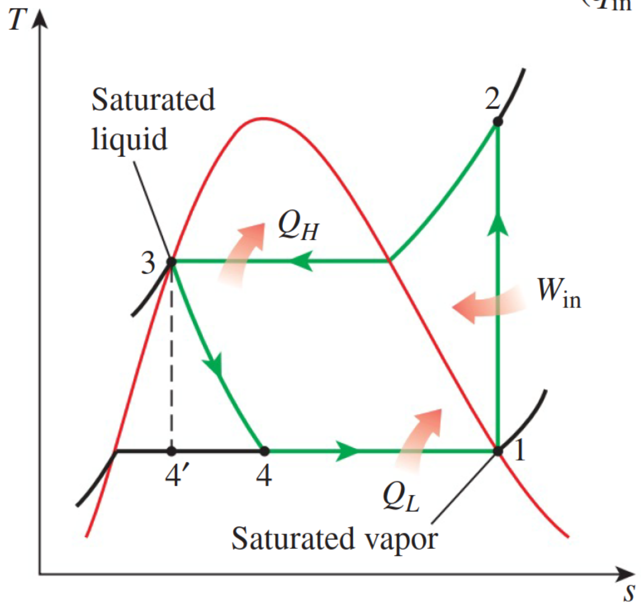


FIGURE 11–3
Schematic and *T*-*s* diagram for the ideal vapor-compression refrigeration cycle.

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i \quad \textbf{(11–6)}$$

$$\mathrm{COP_R} = \frac{q_L}{w_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1} \quad \textbf{(11–7)}$$

$$\mathrm{COP_{HP}} = \frac{q_H}{w_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1} \quad \textbf{(11–8)}$$

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

EXAMPLE 11–1 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.

R134a

$P_L = 0.14$ Mpa

$P_H = 0.8$ Mpa

$\dot{m} = 0.05$ kg/s

a) $\Rightarrow \dot{Q}_L = ?$

$\dot{W}_{in} = ?$

b) $\dot{Q}_H = ?$

c) COP = ?

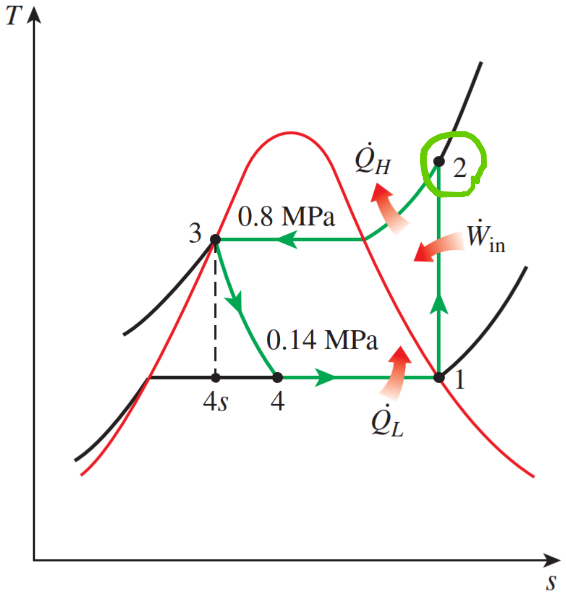


FIGURE 11–6
T-s diagram of the ideal vapor-compression refrigeration cycle described in Example 11–1.

State 1: $\begin{cases} P_1 = 0.14 \text{ Mpa} \\ \text{Sat. vapor} \end{cases} \longrightarrow$ tables

Saturated refrigerant-134a—Pressure table

		Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
60	−36.95	0.0007098	0.31121	3.798	205.32	209.12	3.841	223.95	227.79	0.01634	0.94807	0.96441
70	−33.87	0.0007144	0.26929	7.680	203.20	210.88	7.730	222.00	229.73	0.03267	0.92775	0.96042
80	−31.13	0.0007185	0.23753	11.15	201.30	212.46	11.21	220.25	231.46	0.04711	0.90999	0.95710
90	−28.65	0.0007223	0.21263	14.31	199.57	213.88	14.37	218.65	233.02	0.06008	0.89419	0.95427
100	−26.37	0.0007259	0.19254	17.21	197.98	215.19	17.28	217.16	234.44	0.07188	0.87995	0.95183
120	−22.32	0.0007324	0.16212	22.40	195.11	217.51	22.49	214.48	236.97	0.09275	0.85503	0.94779
140	−18.77	0.0007383	0.14014	26.98	192.57	219.54	27.08	212.08	239.16	0.11087	0.83368	0.94456

State 2: $\begin{cases} P_2 = 0.8 \text{ Mpa} = 800 \text{ kpa} \\ \text{isentropic process in compressor} \end{cases} \rightarrow \boxed{S_2 = S_1}$

tables →

T	v	u	h	s
	P = 0.80 MPa (T_{sat} = 31.31°C)			
Sat.	0.025621	246.79	267.29	0.9183
40	0.027035	254.82	276.45	0.9480
50	0.028547	263.86	286.69	0.9802
60	0.029973	272.83	296.81	1.0110
70	0.031340	281.81	306.88	1.0408

$$P_1 = 0.14 \text{ MPa} \longrightarrow h_1 = h_{g\,@\,0.14\text{ MPa}} = 239.19 \text{ kJ/kg}$$
$$s_1 = s_{g\,@\,0.14\text{ MPa}} = 0.94467 \text{ kJ/kg·K}$$

$$\left.\begin{aligned} P_2 &= 0.8 \text{ MPa} \\ s_2 &= s_1 \end{aligned}\right\} h_2 = 275.40 \text{ kJ/kg}$$

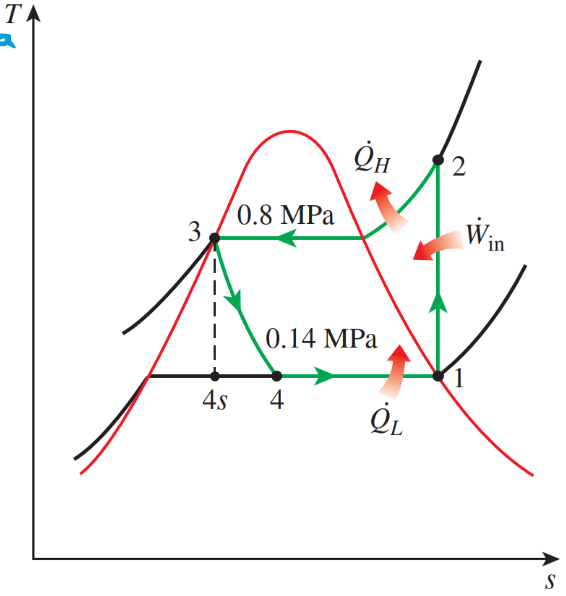
$$P_3 = 0.8 \text{ MPa} \longrightarrow h_3 = h_{f\,@\,0.8\text{ MPa}} = 95.48 \text{ kJ/kg}$$

$$h_4 \cong h_3 \text{ (throttling)} \longrightarrow h_4 = 95.48 \text{ kJ/kg}$$

State 3: $\begin{cases} P_3 = P_2 = 0.8 \text{ MPa} \\ \text{Sat. liquid} \end{cases}$

State 4: $\begin{cases} \text{throttling} \\ \text{valve} \end{cases}$

$h_4 \cong h_3$



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

$$\dot{Q}_L = \dot{m}(h_1 - h_4) = (0.05 \text{ kg/s})[(239.19 - 95.48) \text{ kJ/kg}] = \mathbf{7.19 \text{ kW}}$$

and

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) = (0.05 \text{ kg/s})[(275.40 - 239.19) \text{ kJ/kg}] = \mathbf{1.81 \text{ kW}}$$

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

$$\dot{Q}_H = \dot{m}(h_2 - h_3) = (0.05 \text{ kg/s})[(275.40 - 95.48) \text{ kJ/kg}] = \mathbf{9.00 \text{ kW}}$$

It could also be determined from

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{in} = 7.19 + 1.81 = 9.00 \text{ kW}$$

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

$$\text{COP}_R = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{7.19 \text{ kW}}{1.81 \text{ kW}} = \mathbf{3.97}$$

That is, this refrigerator removes about 4 units of thermal energy from the refrigerated space for each unit of electric energy it consumes.

A throttling process is a thermodynamic process, in which the enthalpy of the gas or medium remains constant (h = const). In fact, the throttling process is one of isenthalpic processes. During the throttling process no work is done by or on the system (dW = 0), and usually there is no heat tranfer (adiabatic) from or into the system (dQ = 0). On the other the throttling process cannot be isentropic, it is a fundamentally irreversible process.

$$\eta_c = \frac{h_{2s} - h_1}{h_2 - h_1}$$

isentropic efficiency of the compressor

ACTUAL VAPOR-COMPRESSION REFRIGERATION CYCLE

Two common sources of irreversibilities are fluid friction (causes pressure drops) and heat transfer to or from the surroundings.

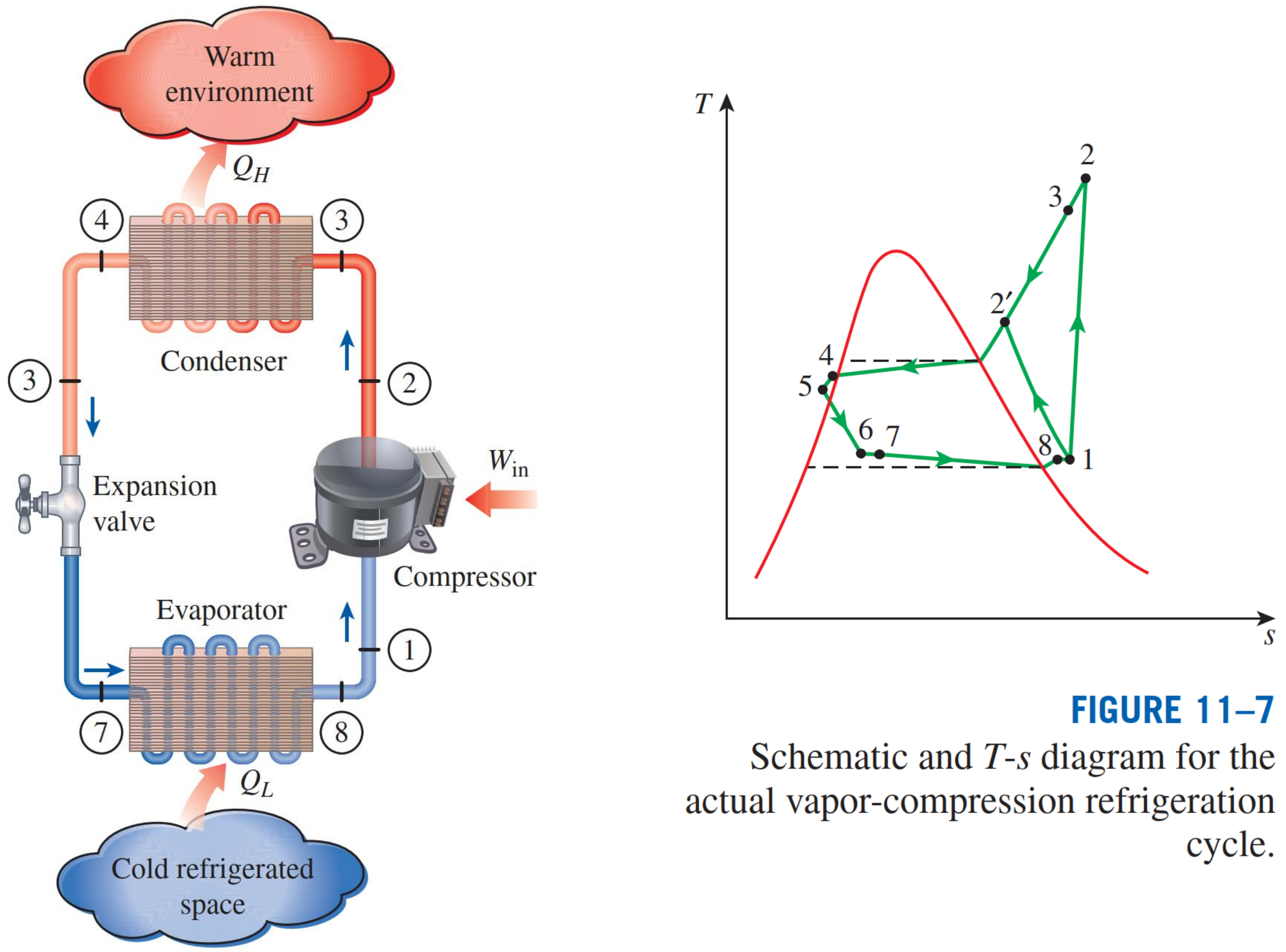


FIGURE 11–7

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

EXAMPLE 11–2 **The Actual Vapor-Compression Refrigeration Cycle**

Refrigerant-134a enters the compressor of a refrigerator as superheated vapor at 0.14 MPa and −10°C at a rate of 0.05 kg/s and leaves at 0.8 MPa and 50°C. The refrigerant is cooled in the condenser to 26°C 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 coefficient of performance of the refrigerator.

Refrigerant: R-134a

a) $\dot{Q}_L = ?$

$\dot{W}_{in} = ?$

b) $\eta_c = ?$

c) COP = ?

State 1: $\begin{cases} P = 0.14 \text{ MPa} \\ T = -10\,^\circ\text{C} \end{cases}$ → table

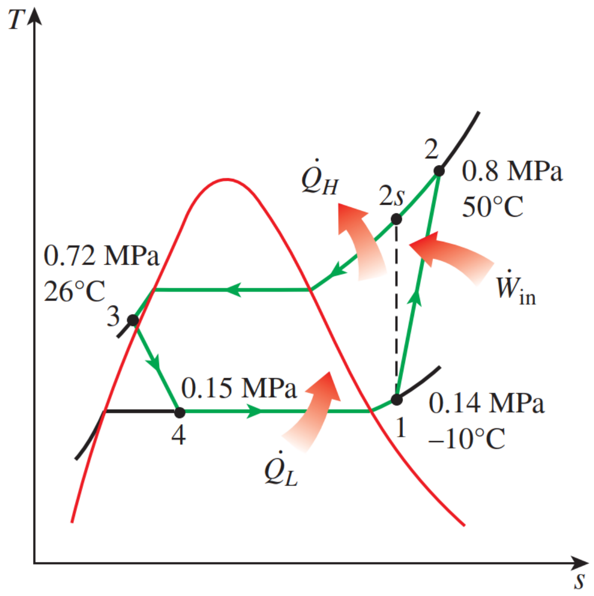


FIGURE 11–8
T-s diagram for Example 11–2.

Superheated refrigerant-134a

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	P = 0.06 MPa (T_{sat} = −36.95°C)				P = 0.10 MPa (T_{sat} = −26.37°C)				P = 0.14 MPa (T_{sat} = −18.77°C)			
Sat.	0.31121	209.12	227.79	0.9644	0.19254	215.19	234.44	0.9518	0.14014	219.54	239.16	0.9446
−20	0.33608	220.60	240.76	1.0174	0.19841	219.66	239.50	0.9721				
−10	0.35048	227.55	248.58	1.0477	0.20743	226.75	247.49	1.0030	0.14605	225.91	246.36	0.9724

State 2: $\begin{cases} P_2 = 0.8 \text{ MPa} \\ T_2 = 50\,^\circ\text{C} \end{cases}$

	P = 0.80 MPa (T_{sat} = 31.31°C)			
Sat.	0.025621	246.79	267.29	0.9183
40	0.027035	254.82	276.45	0.9480
50	0.028547	263.86	286.69	0.9802

$$\left.\begin{aligned} P_1 &= 0.14 \text{ MPa} \\ T_1 &= -10°\text{C} \end{aligned}\right\} \quad h_1 = 246.37 \text{ kJ/kg}$$

$$\left.\begin{aligned} P_2 &= 0.8 \text{ MPa} \\ T_2 &= 50°\text{C} \end{aligned}\right\} \quad h_2 = 286.71 \text{ kJ/kg}$$

$$\left.\begin{aligned} P_3 &= 0.72 \text{ MPa} \\ T_3 &= 26°\text{C} \end{aligned}\right\} \quad h_3 \cong h_{f\,@\,26°\text{C}} = 87.83 \text{ kJ/kg}$$

$$h_4 \cong h_3 \text{ (throttling)} \longrightarrow h_4 = 87.83 \text{ kJ/kg}$$

Saturated refrigerant-134a—Temperature table (*Continued*)

		Specific volume, m³/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			Entropy, kJ/kg · K		
Temp., T °C	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
20	572.07	0.0008161	0.035969	78.86	162.16	241.02	79.32	182.27	261.59	0.30063	0.62172	0.92234
22	608.27	0.0008210	0.033828	81.64	160.42	242.06	82.14	180.49	262.64	0.31011	0.61149	0.92160
24	646.18	0.0008261	0.031834	84.44	158.65	243.10	84.98	178.69	263.67	0.31958	0.60130	0.92088
26	685.84	0.0008313	0.029976	87.26	156.87	244.12	87.83	176.85	264.68	0.32903	0.59115	0.92018

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

$$\dot{Q}_L = \dot{m}(h_1 - h_4) = (0.05 \text{ kg/s})[(246.37 - 87.83) \text{ kJ/kg}] = \mathbf{7.93 \text{ kW}}$$

and

$$\dot{W}_{in} = \dot{m}(h_2 - h_1) = (0.05 \text{ kg/s})[(286.71 - 246.37) \text{ kJ/kg}] = \mathbf{2.02 \text{ kW}}$$

(*b*) The isentropic efficiency of the compressor is determined from

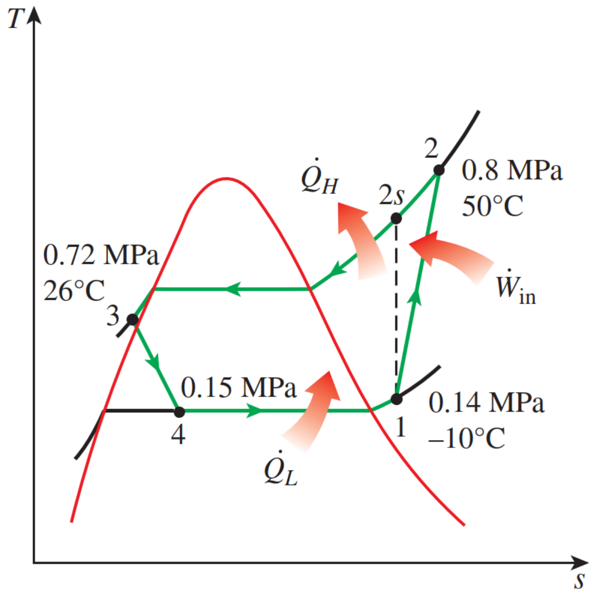
$$\eta_C \cong \frac{h_{2s} - h_1}{h_2 - h_1}$$

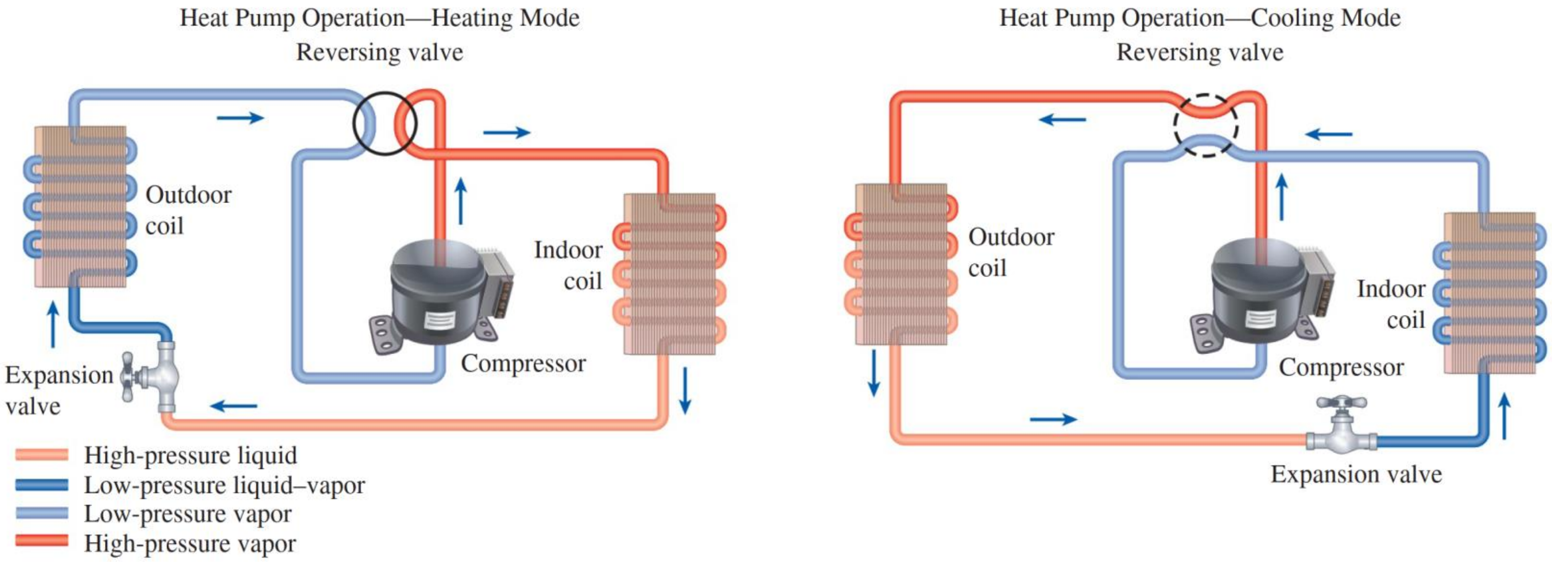
where the enthalpy at state 2*s* (P_{2s} = 0.8 MPa and $s_{2s} = s_1$ = 0.9724 kJ/kg·K) is 284.20 kJ/kg. Thus,

$$\eta_C = \frac{284.20 - 246.37}{286.71 - 246.37} = \mathbf{0.938} \text{ or } \mathbf{93.8\%}$$

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

$$\text{COP}_R = \frac{\dot{Q}_L}{\dot{W}_{in}} = \frac{7.93 \text{ kW}}{2.02 \text{ kW}} = \mathbf{3.93}$$





HEAT PUMP SYSTEMS

Geothermal Heat Pump

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.

INNOVATIVE VAPOR-COMPRESSION REFRIGERATION SYSTEMS

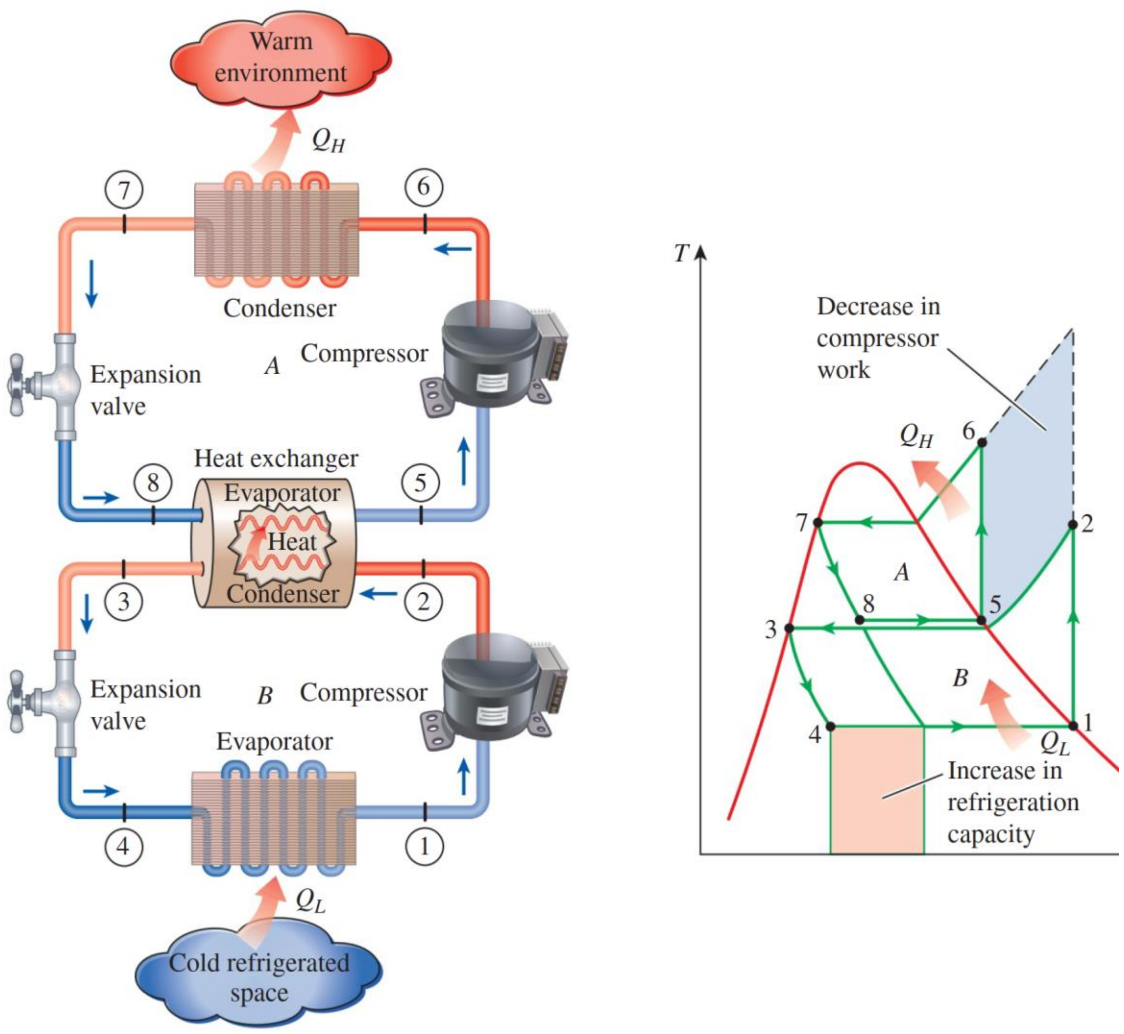


FIGURE 11–12
A two-stage cascade refrigeration system with the same refrigerant in both stages.

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.

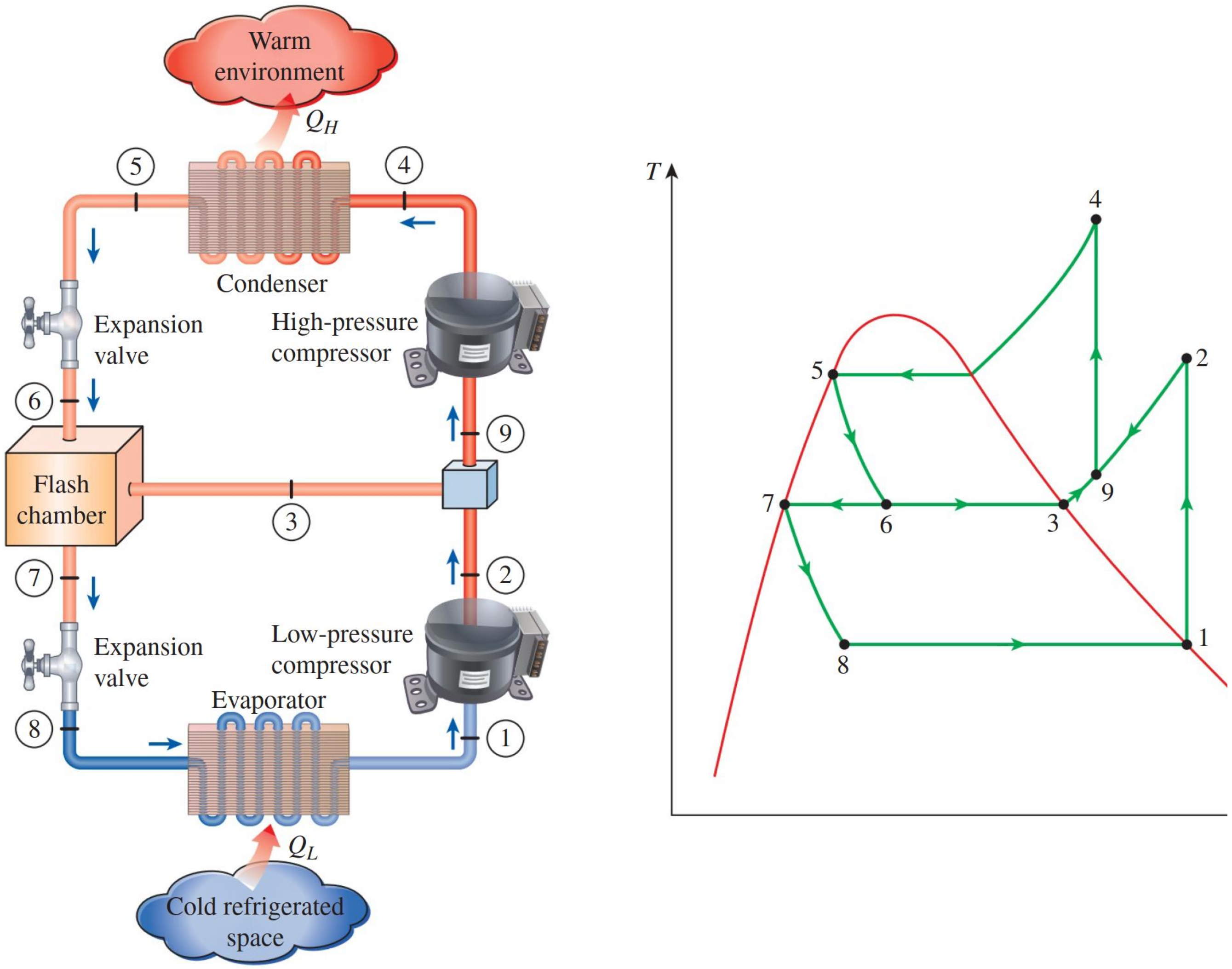
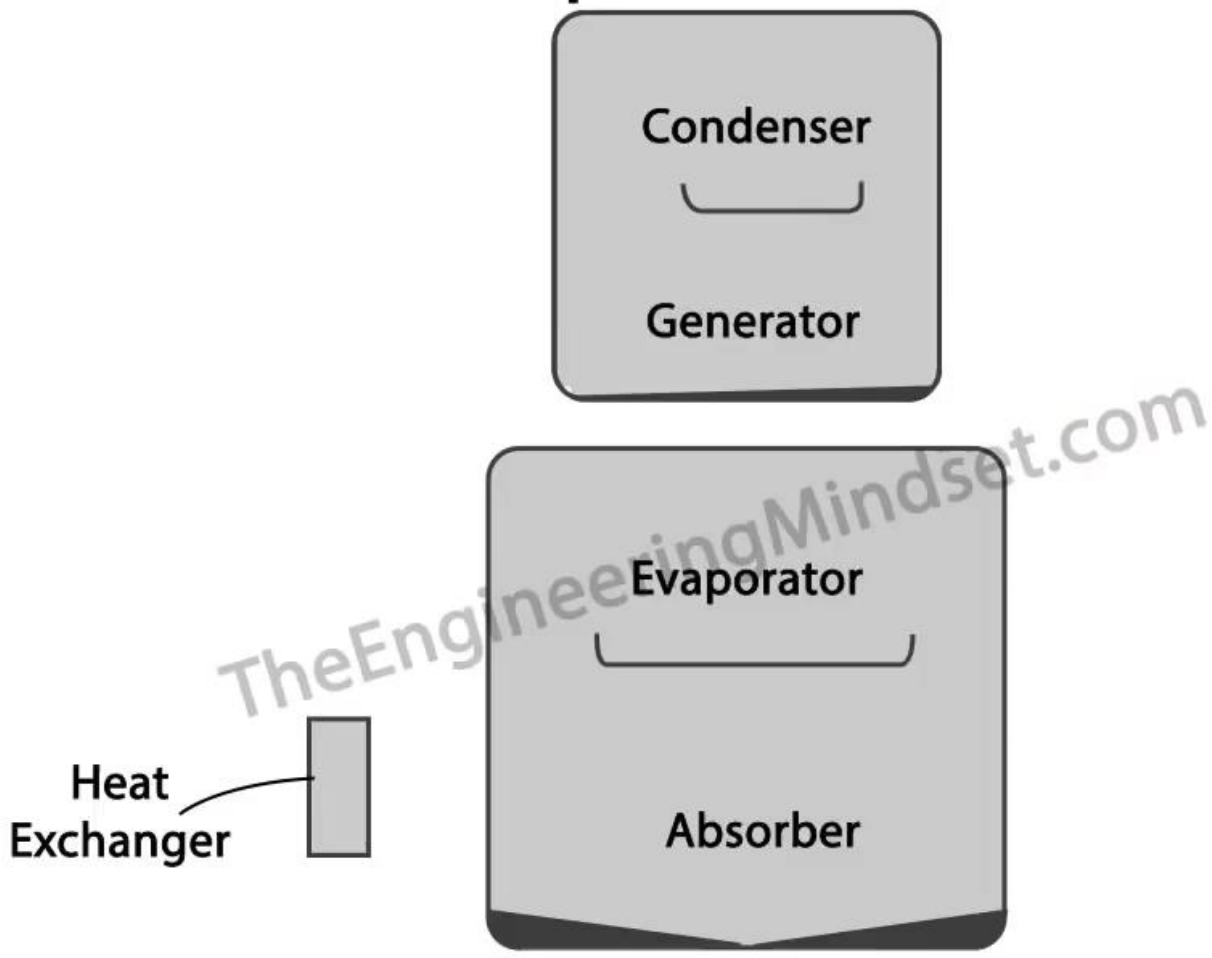
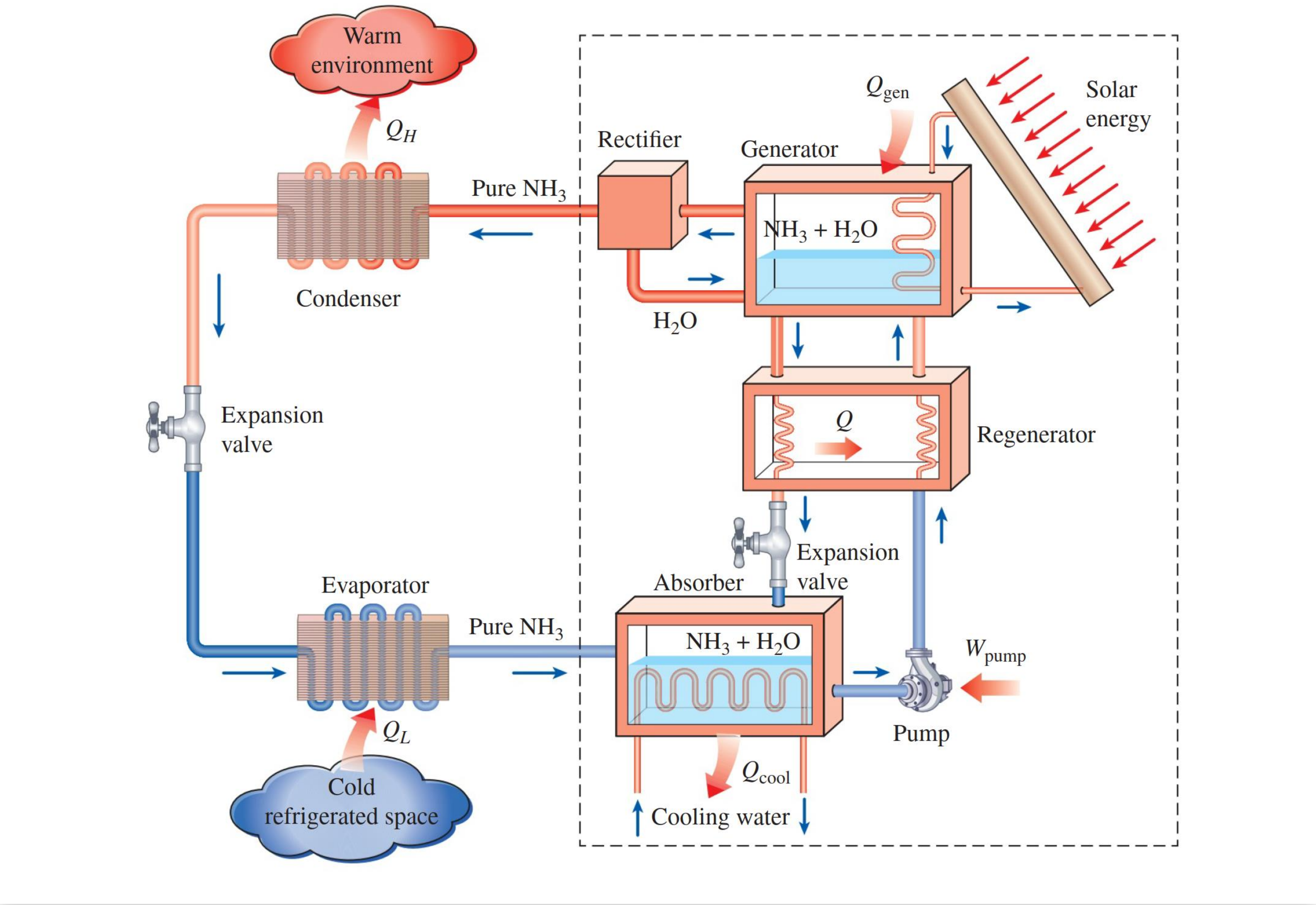


FIGURE 11–14
A two-stage compression refrigeration system with a flash chamber.

How Absorption Chillers Works



Ammonia (NH3) serves as the refrigerant and water (H2O) as the transport medium



ABSORPTION REFRIGERATION SYSTEMS

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

Thank you

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