Chapter 11

REFRIGERATION CYCLES

Thermodynamics: An Engineering Approach
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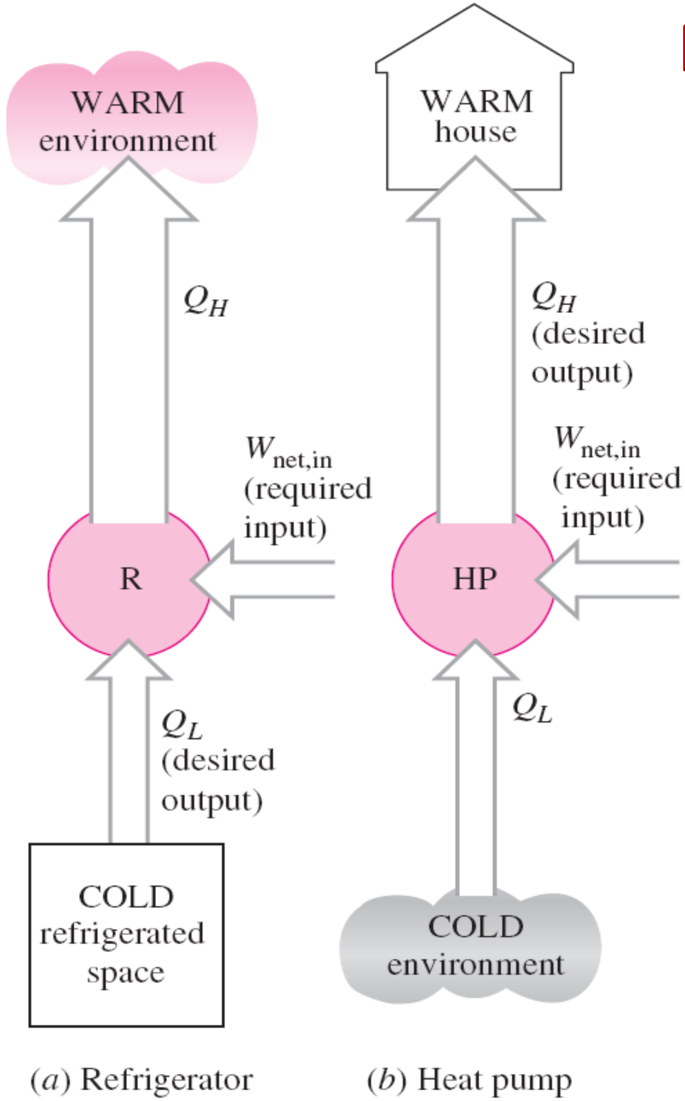
REFRIGERATORS AND HEAT PUMPS



- The transfer of heat from a low-temperature region to a high-temperature one requires special devices called **refrigerators.**
- Refrigerators and heat pumps are ***essentially the same devices***; they differ in their objectives only.

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

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

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

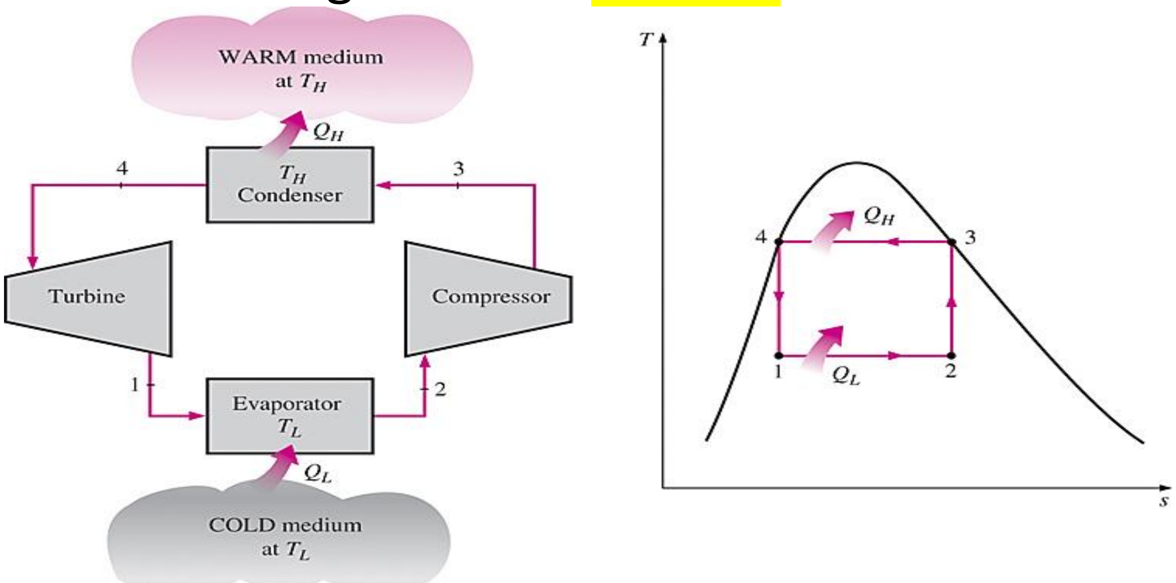
for fixed values of Q_L and Q_H

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

- The **reversed Carnot cycle** is the *most efficient* refrigeration cycle operating between T_L *and* T_H.
- However, it is **not a suitable model** for refrigeration cycles since *processes 2-3 and 4-1 are not practical:*

  1. **Process 2-3** involves the compression of a liquid–vapor mixture, which requires a compressor that will handle two phases, and
  2. **Process 4-1** involves the expansion of high-moisture-content refrigerant in a turbine.



Schematic of a Carnot refrigerator and *T-s* diagram of the reversed Carnot cycle.

$$\mathrm{COP}_{\mathrm{R,Carnot}} = \frac{1}{T_H/T_L - 1}$$

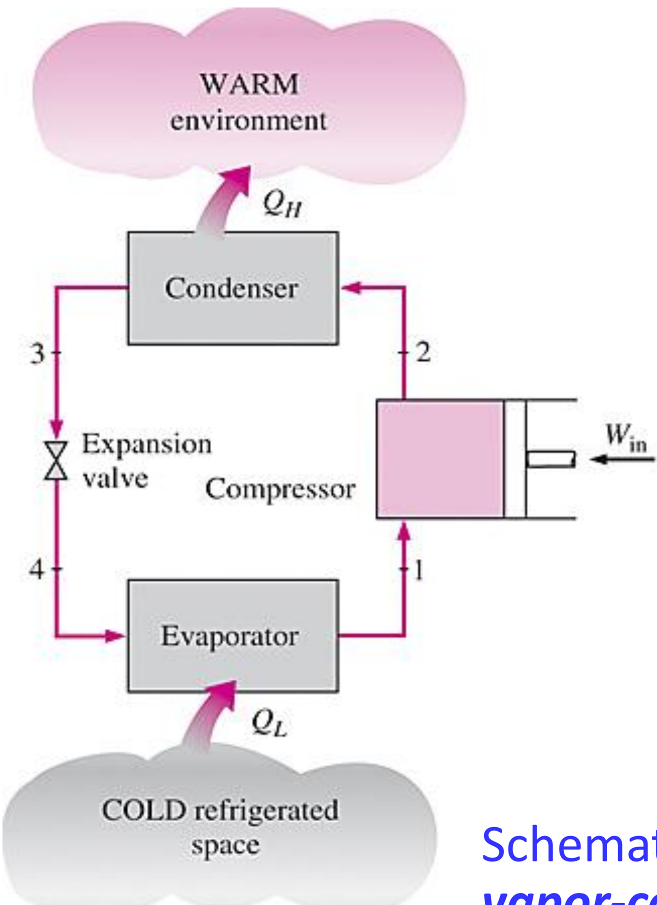
$$\mathrm{COP}_{\mathrm{HP,Carnot}} = \frac{1}{1 - T_L/T_H}$$

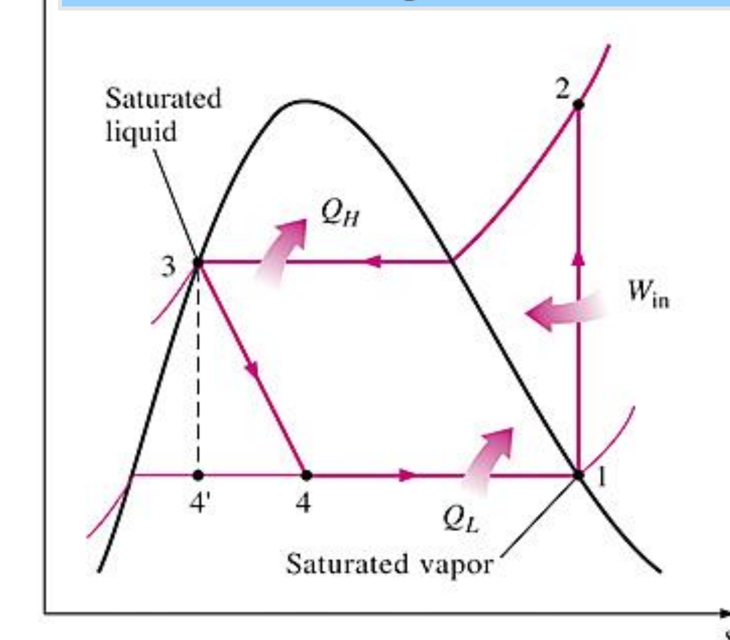
Both COPs increase as the difference between the two temperatures decreases, that is, as T_L rises or T_H falls.

THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE-1

- The **vapor-compression refrigeration cycle** is the ideal model for refrigeration systems.
- Unlike the reversed Carnot cycle, the refrigerant is vaporized completely before it is compressed, and the turbine is replaced with a ***throttling device.***

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





This is the most widely used cycle for refrigerators, A-C systems, and heat pumps.

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

THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE-2

- The ideal vapor-compression refrigeration cycle involves an *irreversible* (throttling) process to make it a more realistic model for the actual systems. [Throttling in NOT isentropic]
- Replacing the expansion valve by a turbine is *not practical* since the added benefits cannot justify the added *cost and complexity*.

Steady-flow energy balance:

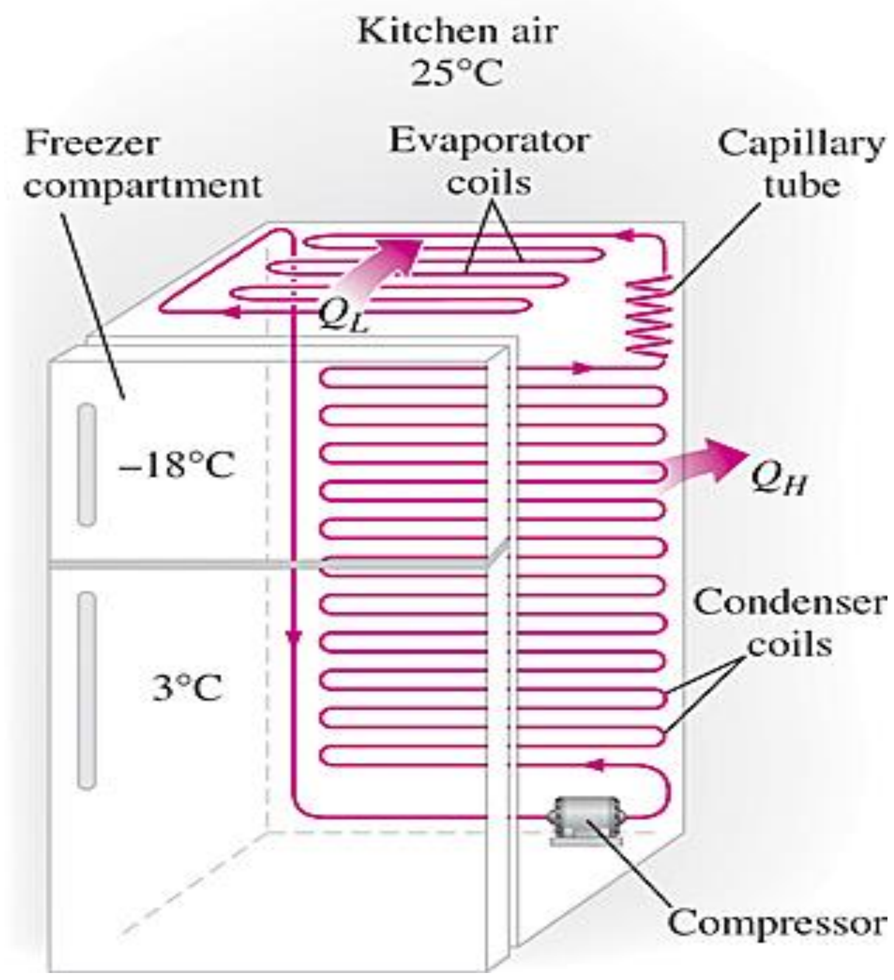
$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i$$

$$\text{COP}_R = \frac{q_L}{w_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1}$$

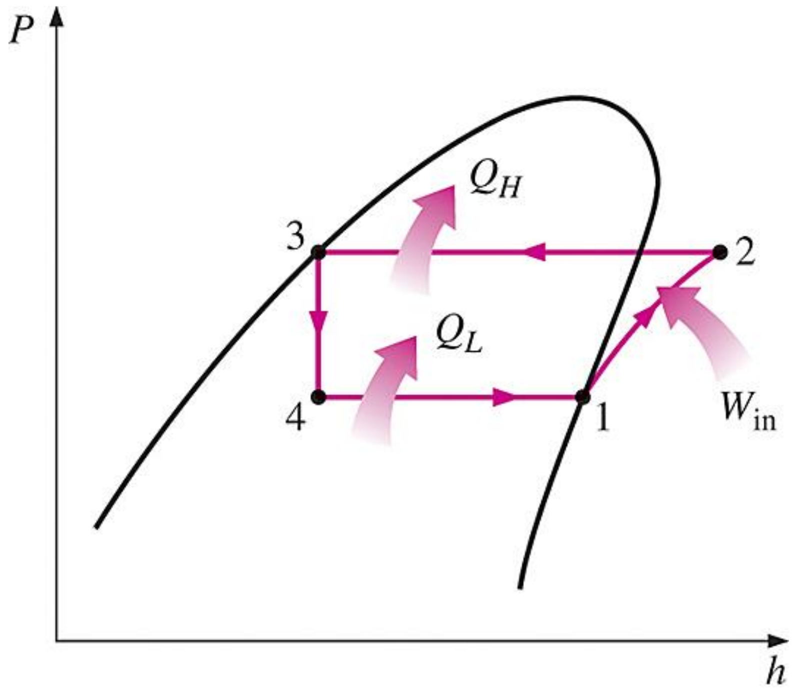
$$\text{COP}_{HP} = \frac{q_H}{w_{net,in}} = \frac{h_2 - h_3}{h_2 - h_1}$$

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

THE IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLE-3



An ordinary household refrigerator.

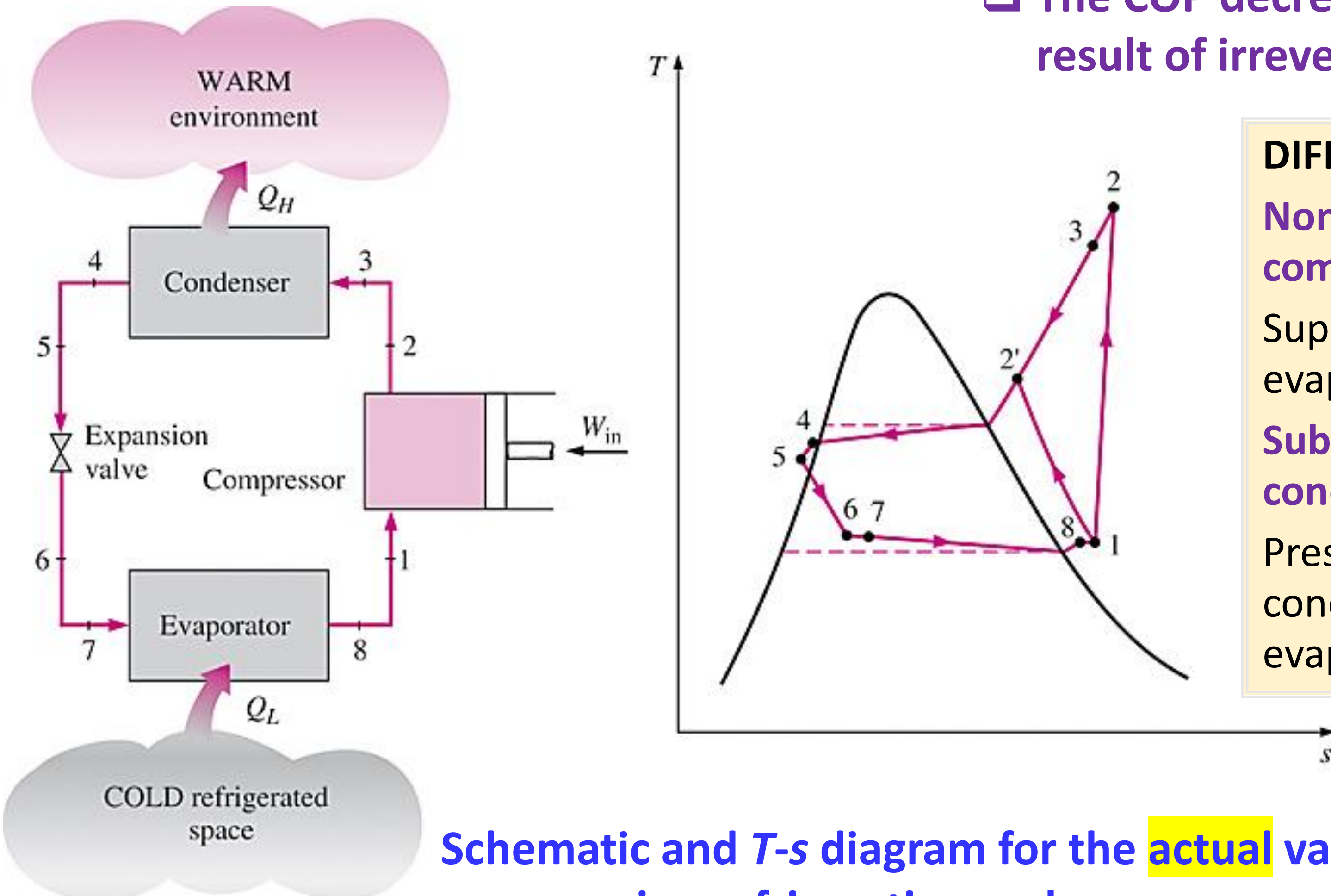


The *P-h* diagram of an ideal vapor-compression refrigeration cycle.

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, 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.

SELECTING THE RIGHT REFRIGERANT

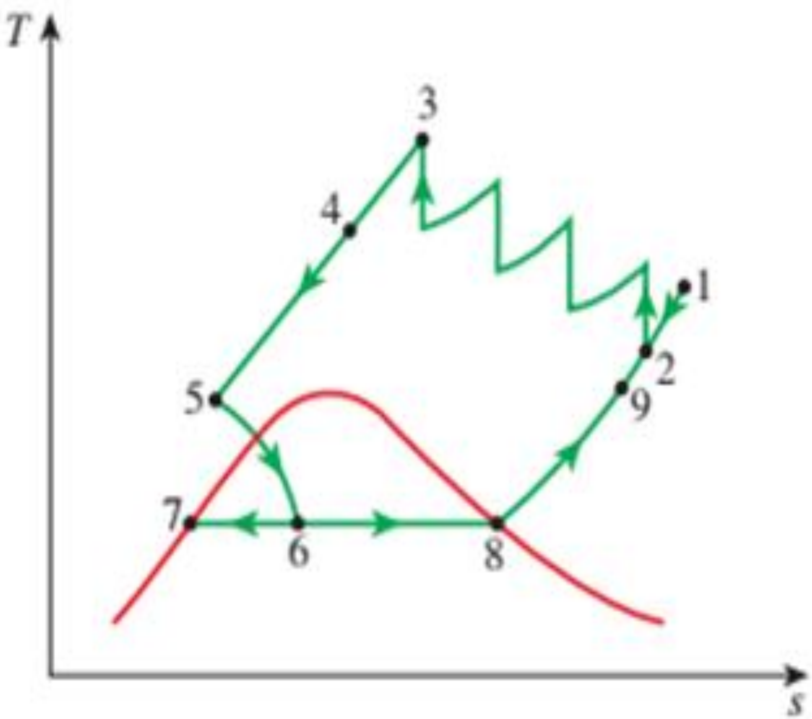
1) Several refrigerants used in refrigeration systems: **Chlorofluorocarbons** (CFCs), ammonia, hydrocarbons (propane, ethane, etc.), carbon dioxide, air (in air-conditioning of aircraft), and even water (in applications above the freezing point).
2) R-11, R-12, R-22, R-134a, and R-502 account for over 90 percent of the market.
3) The industrial and heavy-commercial sectors use ***ammonia*** (it is toxic).
4) R-11 is used in large-capacity water chillers serving A-C systems in buildings.
5) **R-134a** (replaced R-12, which damages ozone layer) is used in domestic refrigerators and freezers, as well as automotive air conditioners.
6) 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.
7) R-502 (a blend of R-115 and R-22) is the dominant refrigerant used in commercial refrigeration systems such as those in supermarkets.
8) ***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. Fully halogenated CFCs (such as R-11, R-12, and R-115) do the most damage to the ozone layer. Refrigerants that are friendly to the ozone layer have been developed.
9) **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.

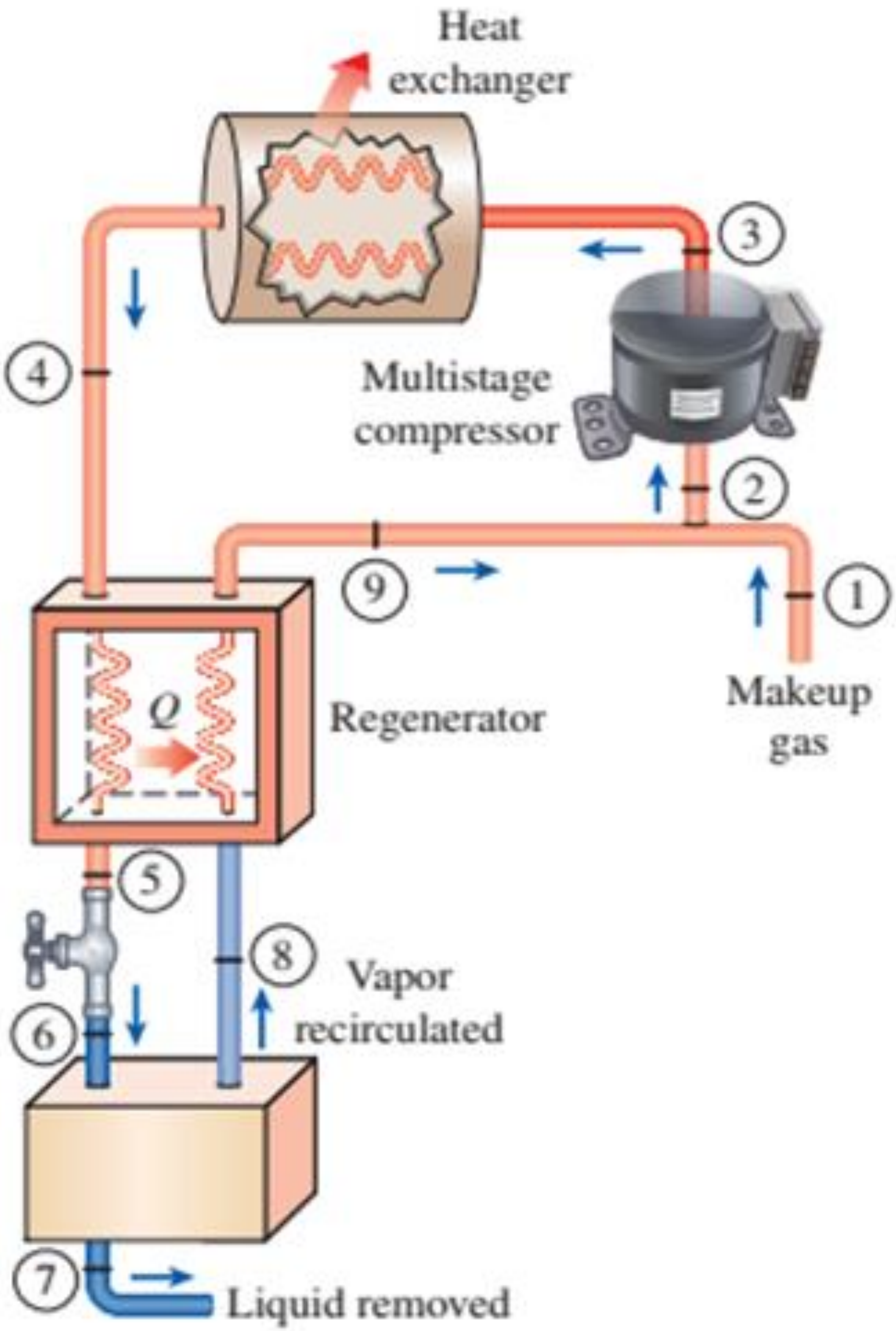
Liquefaction of Gases

- Many important scientific and engineering processes at **cryogenic temperatures** (below about 100°C) depend on liquefied gases including:
  - 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 superconductivity.
- The storage of gases (hydrogen) and transportation of some gases (natural gas, i.e., methane & ethane) are done after they are liquefied at very low temperatures.
- Several innovative **cycles** are used for the liquefaction of gases, including the popular Linde-Hampson system for liquefying gases (Next).

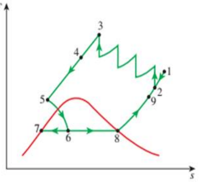
Liquefaction of Gases

Linde-Hampson system for liquefying gases





Description of Linde-Hampson Liquefaction Process:



1) 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**.
2) The compression process approaches an **isothermal process** due to intercooling.
3) High-pressure gas is cooled in an aftercooler by a cooling medium or by a separate external refrigeration system to **state 4**.
4) The gas is further cooled in a regenerative counter-flow heat exchanger by the uncondensed portion of gas (*stream #8*) from the previous cycle to **state 5,** and it is throttled to **state 6**, which is a saturated liquid–vapor mixture state.
5) 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.
6) Finally, the gas is mixed with fresh makeup gas, & cycle is repeated.

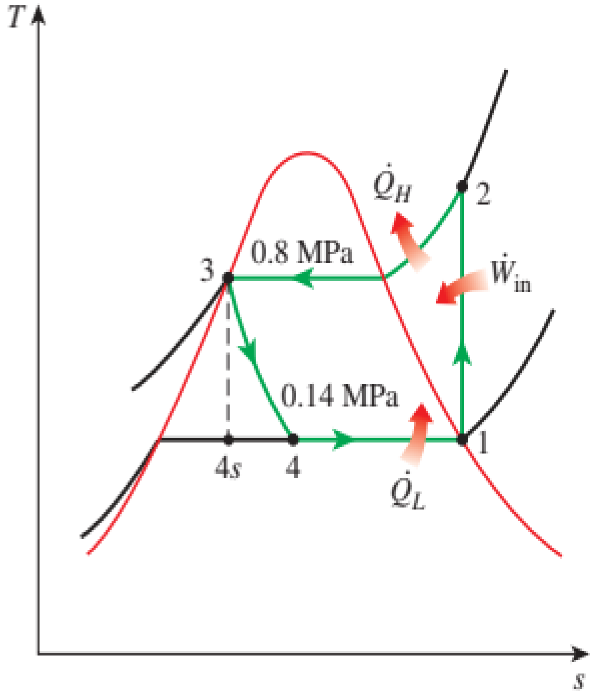


FIGURE 11–6

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

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.

SOLUTION A refrigerator operates on an ideal vapor-compression refrigeration cycle between two specified pressure limits. The rate of refrigeration, the power input, the rate of heat rejection, and the COP are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis The *T-s* diagram of the refrigeration cycle is shown in Fig. 11–6. We note that this is an ideal vapor-compression refrigeration cycle, and thus the compressor is isentropic and the refrigerant leaves the condenser as a saturated liquid and enters the compressor as saturated vapor. From the refrigerant-134a tables, the enthalpies of the refrigerant at all four states are determined as follows:

$$P_1 = 0.14 \text{ MPa} \longrightarrow h_1 = h_{g\,@\,0.14\text{ MPa}} = 239.19 \text{ kJ/kg}$$

$$s_1 = s_{g\,@\,0.14\text{ MPa}} = 0.94467 \text{ kJ/kg·K}$$

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

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

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

(*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

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

(*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

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

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

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

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

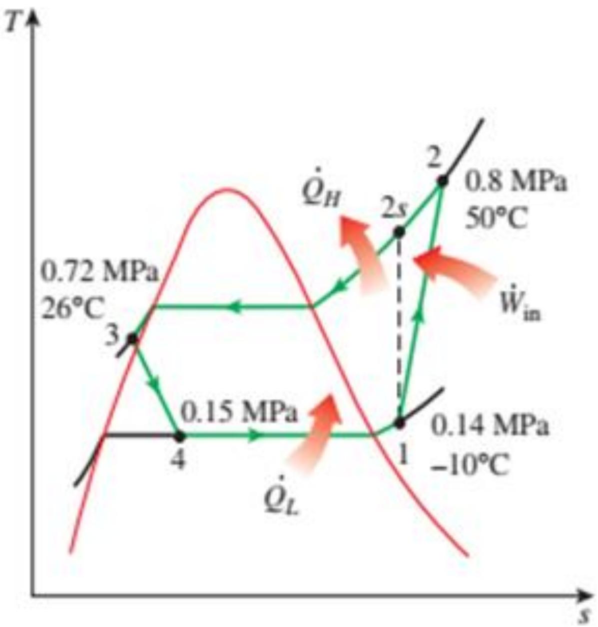


FIGURE 11–8

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.

SOLUTION A refrigerator operating on a vapor-compression cycle is considered. The rate of refrigeration, the power input, the compressor efficiency, and the COP are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

Analysis The *T*-*s* diagram of the refrigeration cycle is shown in Fig. 11–8. We note that the refrigerant leaves the condenser as a compressed liquid and enters the compressor as superheated vapor. The enthalpies of the refrigerant at various states are determined from the refrigerant tables to be

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

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

$$\left.\begin{array}{l} P_2 = 0.8 \text{ MPa} \\ T_2 = 50^\circ\text{C} \end{array}\right\} \quad h_2 = 286.71 \text{ kJ/kg}$$

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

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

(*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

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

(*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

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