Thermodynamics: An Engineering Approach
8th Edition
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Topic 12

SECOND LAW OF THERMODYNAMICS

Objectives

- Introduce the second law of thermodynamics.
- Identify valid processes as those that satisfy both the first and second laws of thermodynamics.
- Discuss the concepts of perpetual-motion machines.
- Discuss the differences between reversible and irreversible processes.
- Apply the second law of thermodynamics to cycles and cyclic devices.
- Apply the second law to develop the absolute thermodynamic temperature scale.
- Describe the Carnot cycle.
- Examine the Carnot principles, idealized Carnot heat engines, refrigerators, and heat pumps.
- Determine the expressions for the thermal efficiencies and coefficients of performance for reversible heat engines, heat pumps, and refrigerators.

INTRODUCTION TO THE SECOND LAW

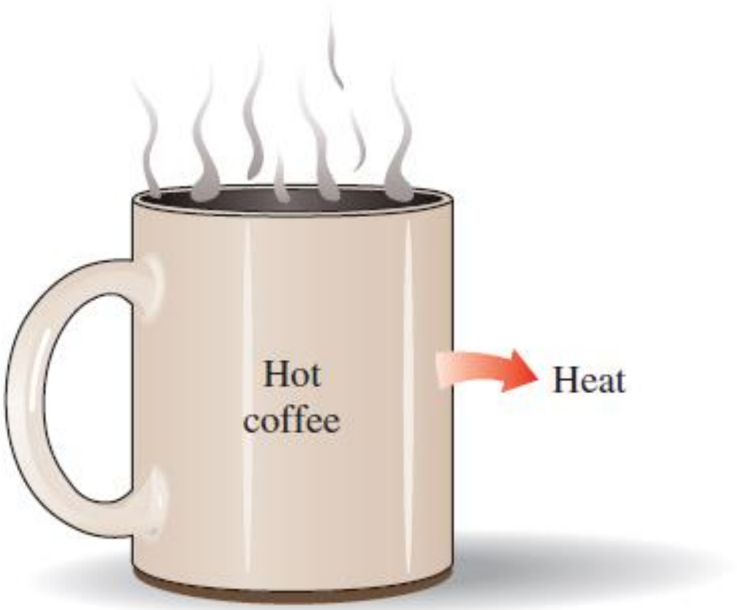


FIGURE 6–1
A cup of hot coffee does not get hotter in a cooler room.

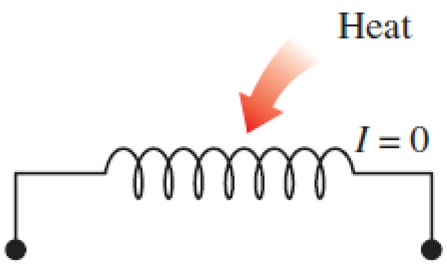


FIGURE 6–2
Transferring heat to a wire will not generate electricity.

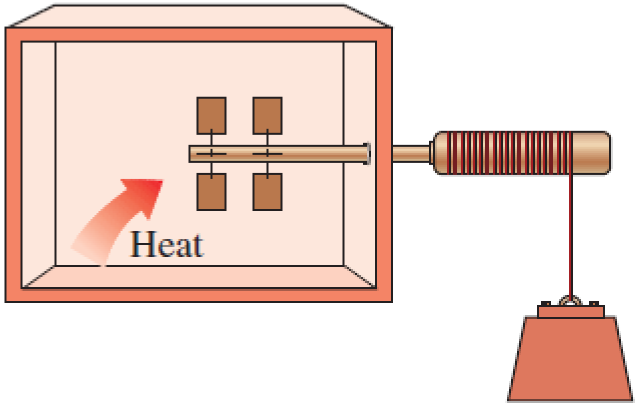


FIGURE 6–3
Transferring heat to a paddle wheel will not cause it to rotate.

These processes cannot occur even though they are not in violation of the first law.

MAJOR USES OF THE SECOND LAW

1. The second law may be used to identify the direction of processes.
2. The second law also asserts that energy has quality as well as quantity. The first law is concerned with the quantity of energy and the transformations of energy from one form to another with no regard to its quality. The second law provides the necessary means to determine the quality as well as the degree of degradation of energy during a process.
3. The second law of thermodynamics is also used in determining the theoretical limits for the performance of commonly used engineering systems, such as heat engines and refrigerators, as well as predicting the degree of completion of chemical reactions.

FIGURE 6–4
Processes occur in a certain direction, and not in the reverse direction.

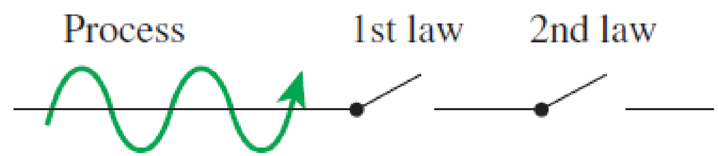


FIGURE 6–5
A process must satisfy both the first and second laws of thermodynamics to proceed.

THERMAL ENERGY RESERVOIRS

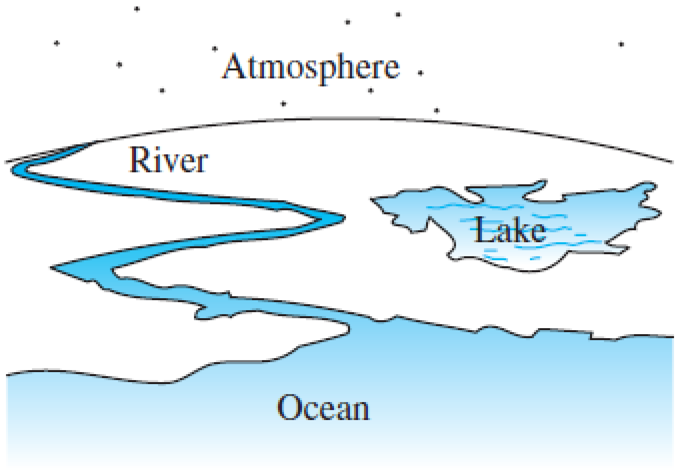


FIGURE 6–6
Bodies with relatively large thermal masses can be modeled as thermal energy reservoirs.

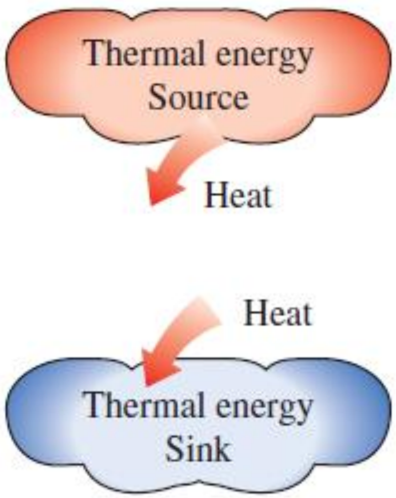


FIGURE 6–7
A source supplies energy in the form of heat, and a sink absorbs it.

- A hypothetical body with a relatively large thermal energy capacity (mass x specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature is called a thermal energy reservoir, or just a **reservoir**.
- In practice, large bodies of water such as oceans, lakes, and rivers as well as the atmospheric air can be modeled accurately as thermal energy reservoirs because of their large thermal energy storage capabilities or thermal masses.

The Second Law of Thermodynamics: Kelvin-Planck Statement

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

No heat engine can have a thermal efficiency of 100 percent, or as *for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace*.

The impossibility of having a 100% efficient heat engine is not due to friction or other dissipative effects. It is a limitation that applies to both the idealized and the actual heat engines.

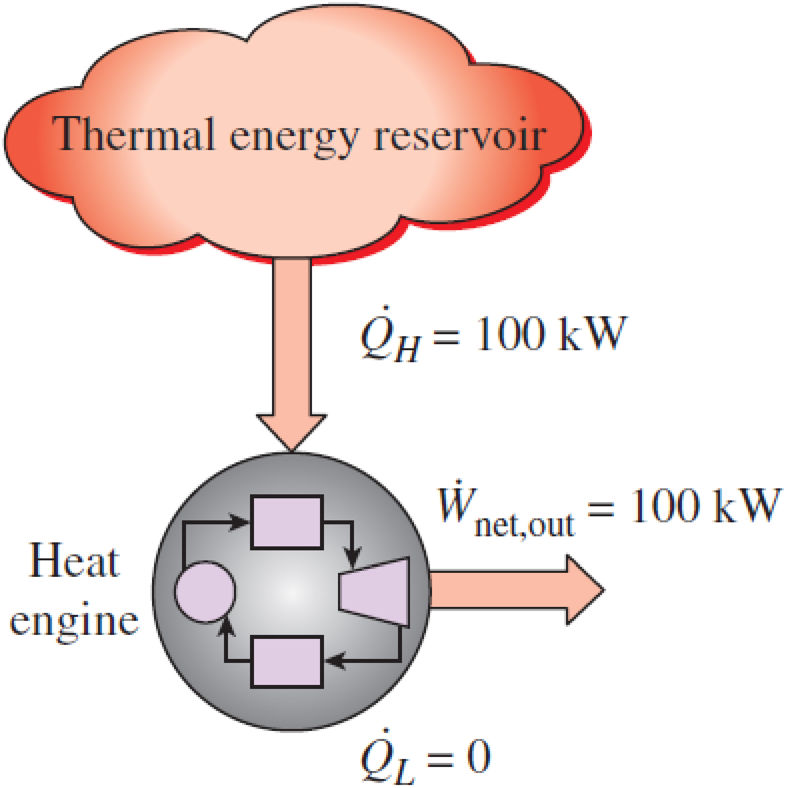


FIGURE 6–18

A heat engine that violates the Kelvin–Planck statement of the second law.

The Second Law of Thermodynamics: Clausius Statement

It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

It states that a refrigerator <u>cannot operate</u> unless its compressor is driven by an <u>external power</u> source, such as an electric motor.

This way, the net effect on the surroundings involves the consumption of some energy in the form of work, in addition to the transfer of heat from a colder body to a warmer one.

To date, no experiment has been conducted that contradicts the second law, and this should be taken as sufficient proof of its validity.

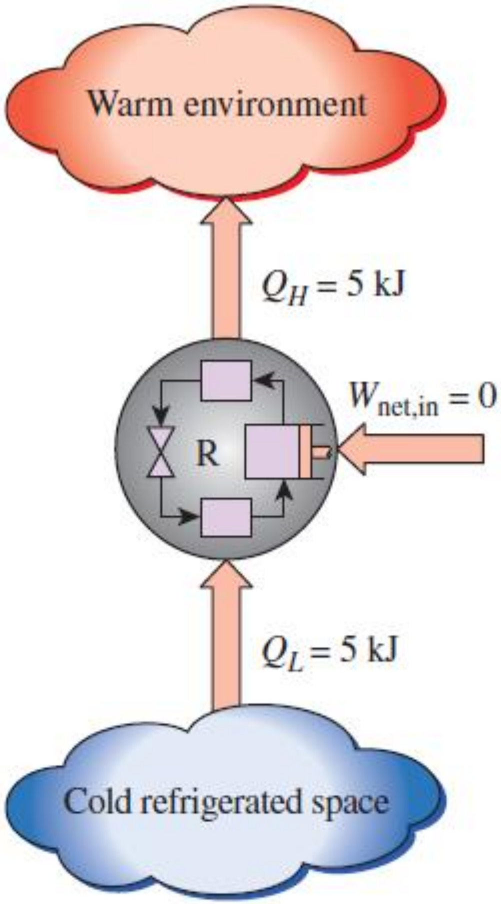


FIGURE 6–25
A refrigerator that violates the Clausius statement of the second law.

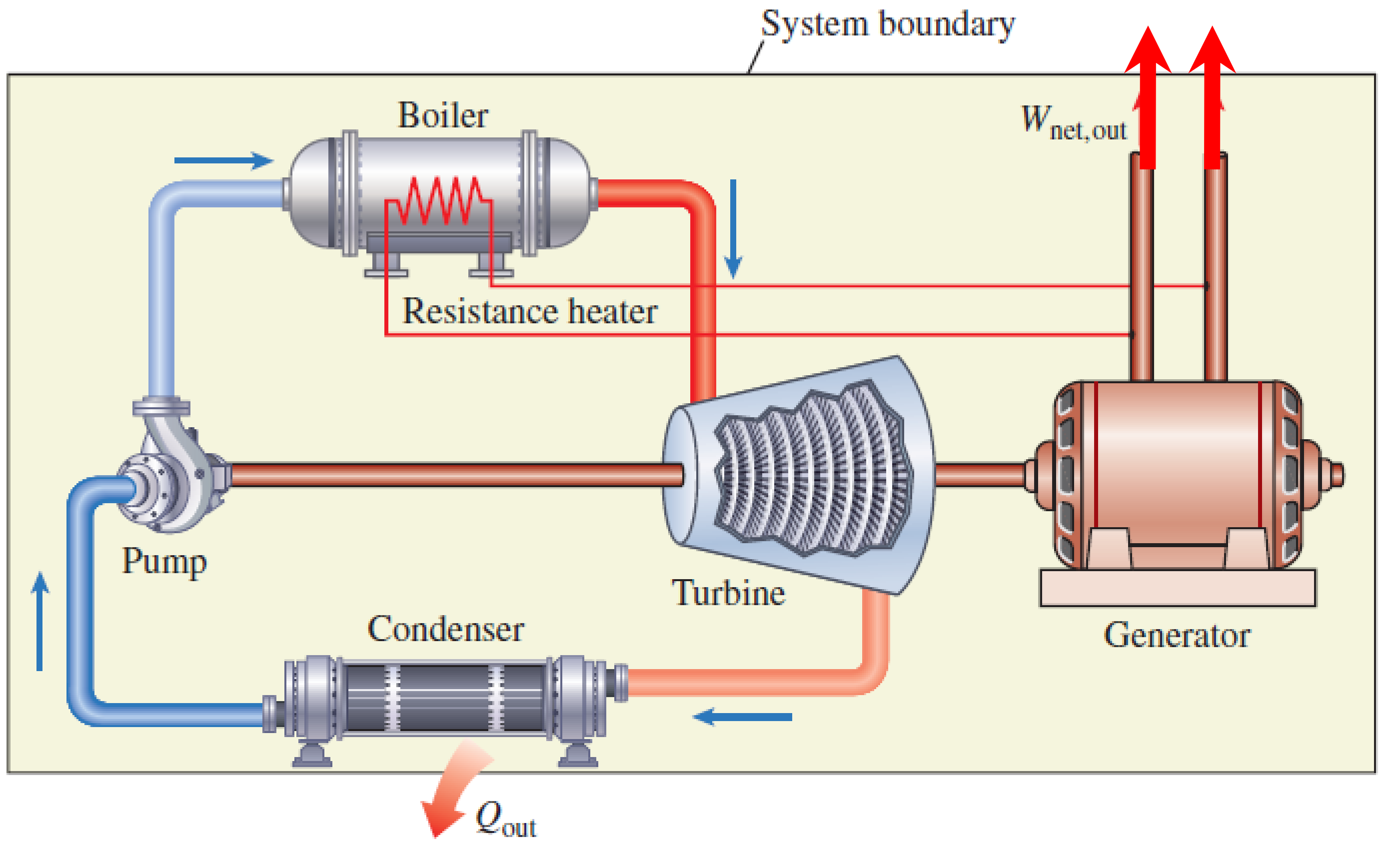


FIGURE 6–27
A perpetual-motion machine that violates the first law of thermodynamics (PMM1).

PERPETUAL-MOTION MACHINES

Perpetual-motion machine**:** Any device that violates the first or the second law.

A device that violates the first law (by *creating* energy) is called a PMM1.

A device that violates the second law is called a PMM2.

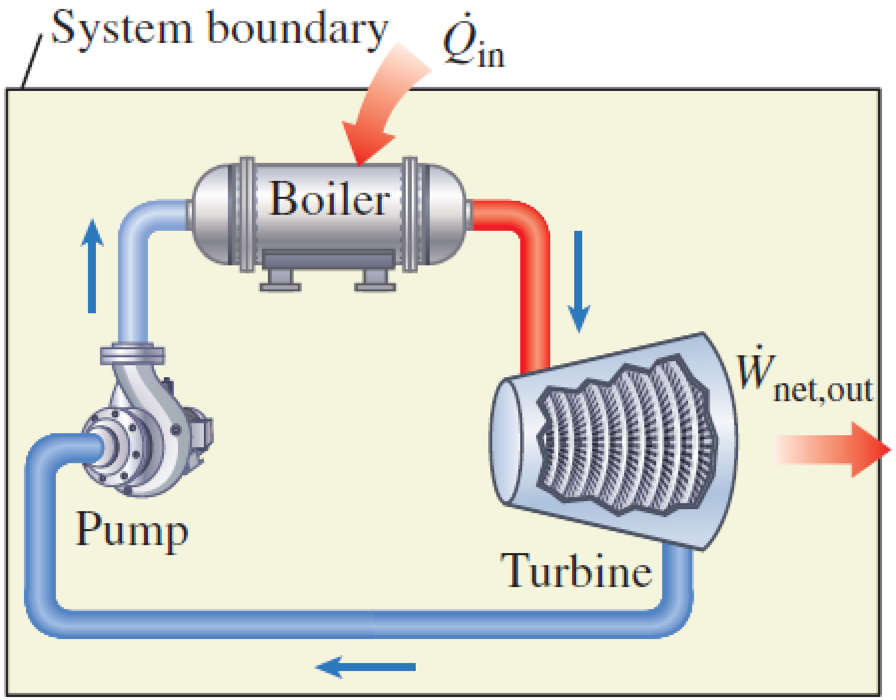


FIGURE 6–28

A perpetual-motion machine that violates the second law of thermodynamics (PMM2).

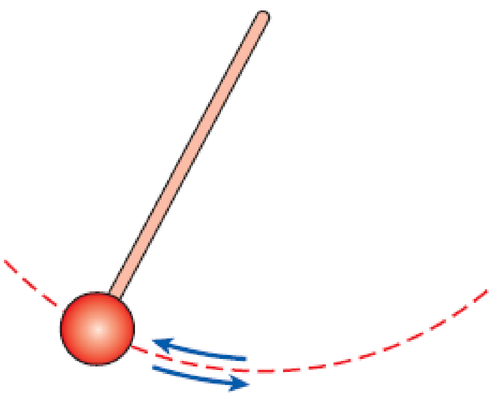
Despite numerous attempts, no perpetual-motion machine is known to have worked.

If something sounds too good to be true, it probably is.

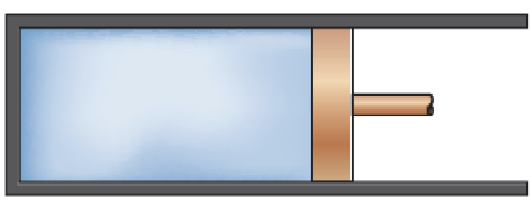
REVERSIBLE AND IRREVERSIBLE PROCESSES

<u>Reversible Process</u>**:** *A process that can be reversed without leaving any trace on the surroundings.*
<u>Irreversible Process</u>**:** A process that is not reversible.

- All the processes occurring in nature are irreversible.
- ***Why are we interested*** **in reversible processes?**
- **(1)** they are <u>easy to analyze</u> and **(2)** they serve as idealized models (<u>theoretical limits</u>) to which actual processes can be compared.
- Some processes are more irreversible than others.
- We try to approximate reversible processes. **Why?**

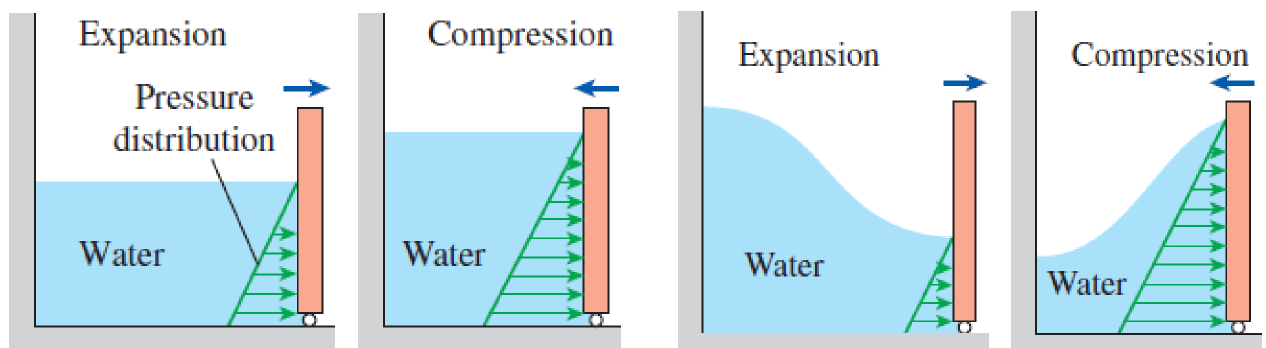


(*a*) Frictionless pendulum



(*b*) Quasi-equilibrium expansion and compression of a gas

FIGURE 6–29
Two familiar reversible processes.



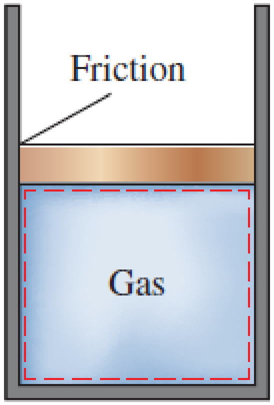
(*a*) Slow (reversible) process

(*b*) Fast (irreversible) process

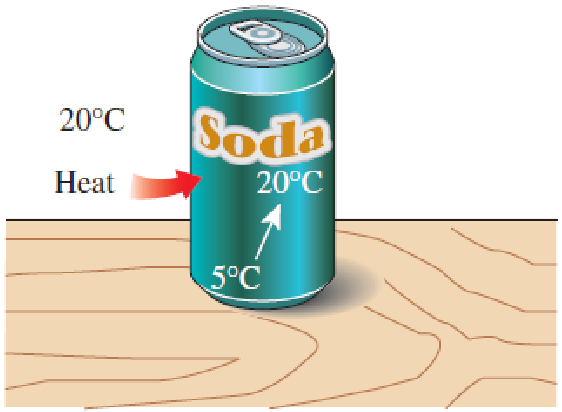
Reversible processes deliver the most and consume the least work.

Irreversibilities

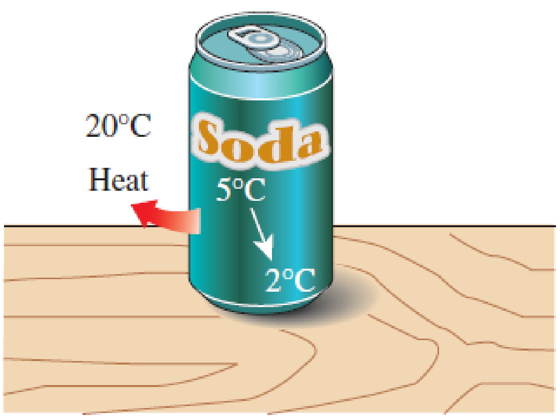
- The factors that cause a process to be irreversible are called irreversibilities.
- They include friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, electric resistance, inelastic deformation of solids, and chemical reactions.
- The presence of any of these effects renders a process irreversible.



Friction renders a process irreversible.

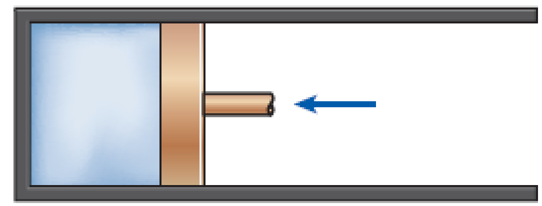


(*a*) An irreversible heat transfer process

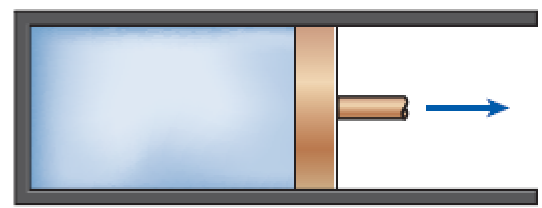


(*b*) An impossible heat transfer process

(*a*) Heat transfer through a temperature difference is irreversible, and (*b*) the reverse process is impossible.



(*a*) Fast compression



(*b*) Fast expansion

(*c*) Unrestrained expansion

Irreversible compression and expansion processes.

Internally and Externally Reversible Processes

- **Internally reversible process:** If no irreversibilities occur within the boundaries of the system during the process.
- **Externally reversible:** If no irreversibilities occur outside the system boundaries.
- **Totally reversible process:** It involves no irreversibilities within the system or its surroundings.
- A totally reversible process involves no heat transfer through a finite temperature difference, no nonquasi-equilibrium changes, and no friction or other dissipative effects.

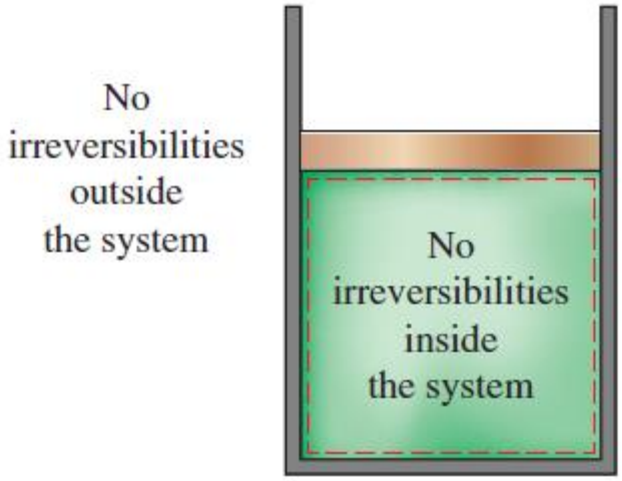


FIGURE 6–34
A reversible process involves no internal and external irreversibilities.

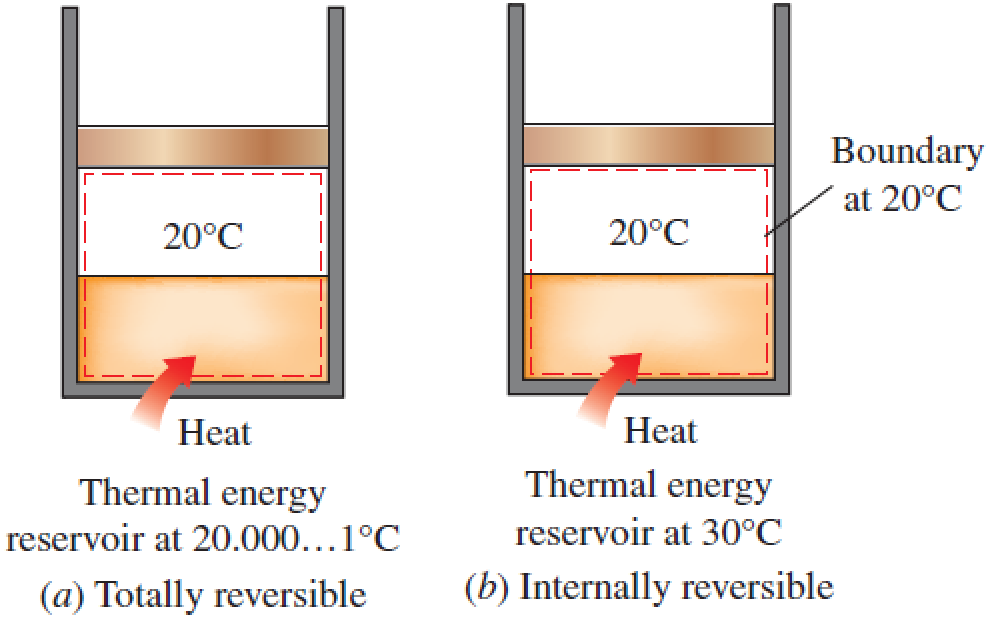


FIGURE 6–35
Totally and internally reversible heat transfer processes.

Review

A coal burning steam power plant produces a net power of 300 MW with an overall thermal efficiency of 32%. The actual air-fuel ratio in the furnace is calculated to be 12 (kg air) : 1 (kg fuel). The heating value of the coal is 28,000 kJ/kg. Determine the amount of coal consumed during a 24 hour period and the rate of air flowing through the furnace.

Example 1

Review

R-134a enters the condenser of a residential heat pump at 800 kPa and 35°C at a rate of 0.018 kg/s and leaves at 800 kPa as a saturated liquid. If the compressor consumes 1.2 kW of power, determine the COP of the heat pump and the rate of heat absorption from the outside air.

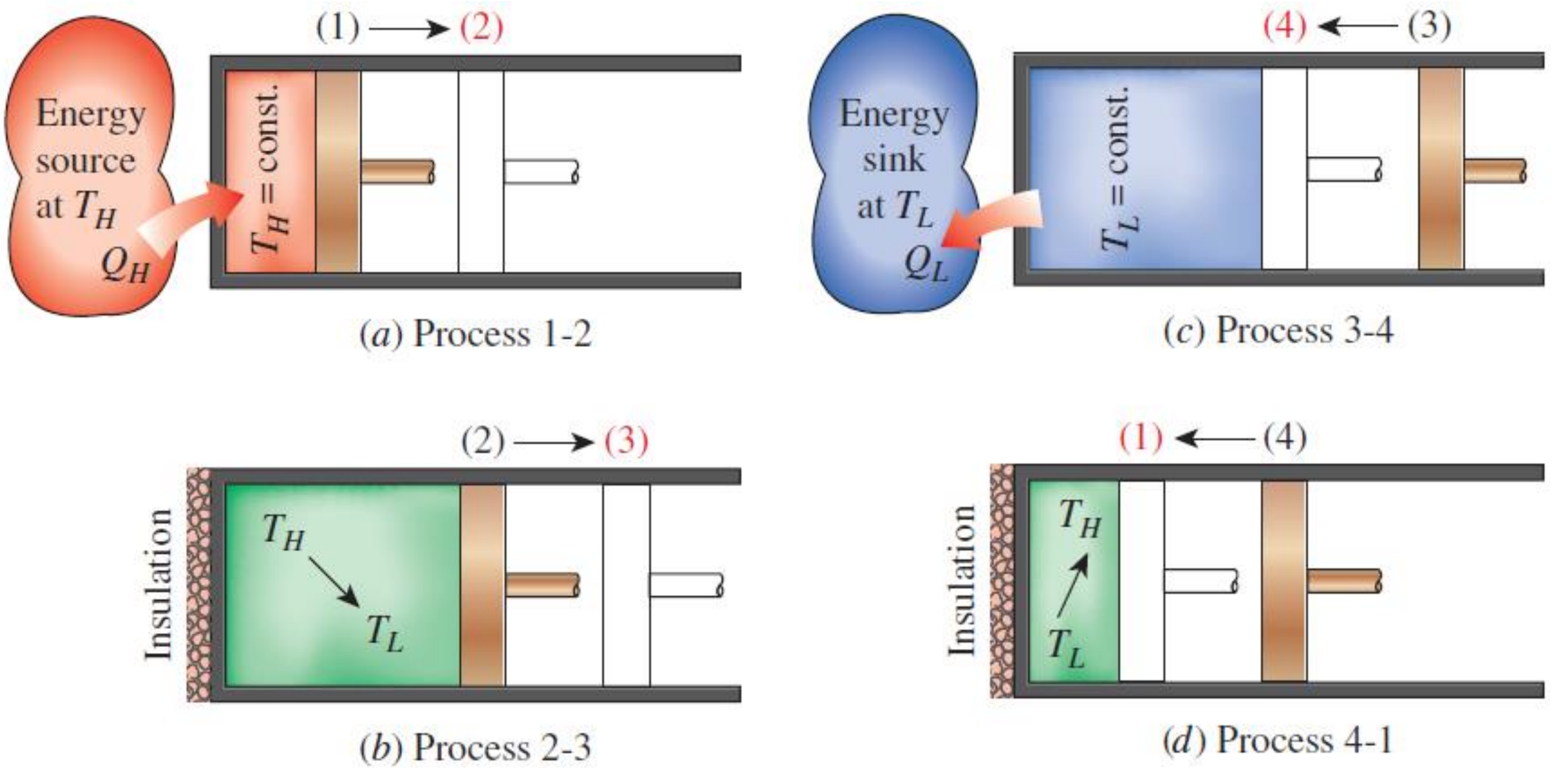
Example 2

Review

Consider a building whose annual air-conditioning load is estimated to be 40,000 kWhr in an area where the unit cost of electricity is $0.10/kWhr. Two air conditioners are considered for the building. Air conditioner A has a seasonal average COP of 2.3 and costs $5,500 to install. Air conditioner B has a seasonal average COP of 3.6 and costs $7,000 to install. In how many years, will the total cost to install and operate be equal between the two conditioners?

$\boxed{\textbf{Example 3}}$

THE CARNOT CYCLE



Execution of the Carnot cycle in a closed system.

Reversible Isothermal Expansion (process 1-2, T_H = constant)
Reversible Adiabatic Expansion (process 2-3, temperature drops from T_H to T_L)
Reversible Isothermal Compression (process 3-4, T_L = constant)
Reversible Adiabatic Compression (process 4-1, temperature rises from T_L to T_H)

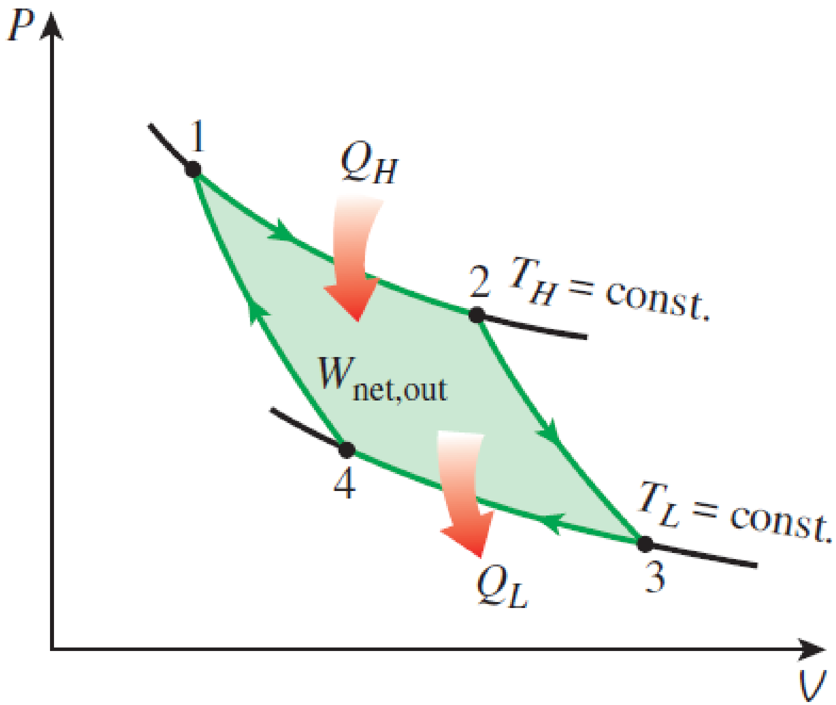


FIGURE 6–37
P-V diagram of the Carnot cycle.

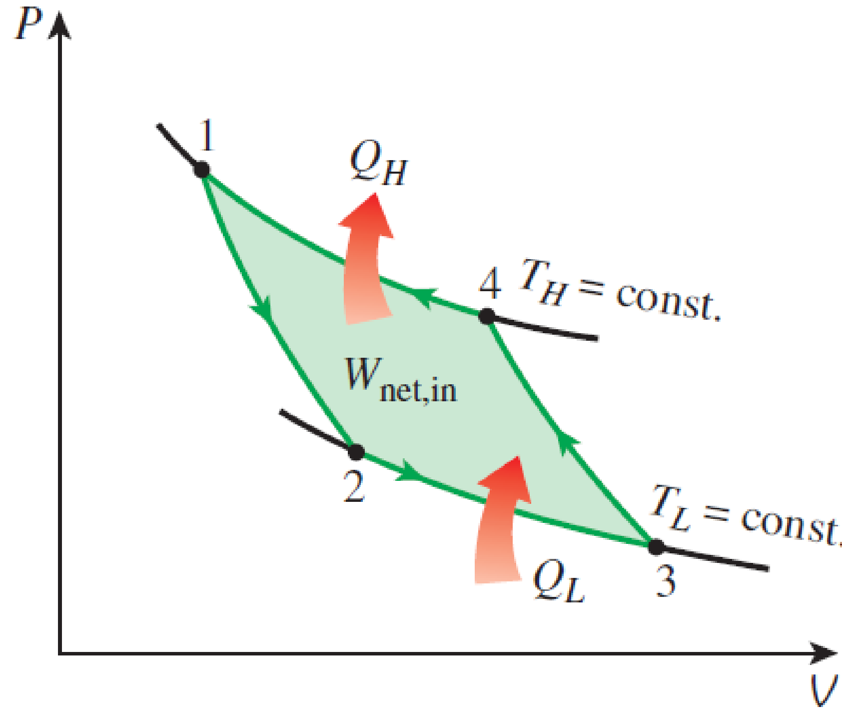


FIGURE 6–38
P-V diagram of the reversed Carnot cycle.

The Reversed Carnot Cycle

The Carnot heat-engine cycle is a totally reversible cycle.

Therefore, all the processes that comprise it can be *reversed*, in which case it becomes the Carnot refrigeration cycle.

THE CARNOT PRINCIPLES

1. The efficiency of an <u>irreversible</u> heat engine is <u>always less</u> than the efficiency of a reversible one operating between the same two reservoirs.
2. The efficiencies of all reversible heat engines operating between the same two reservoirs are the same.

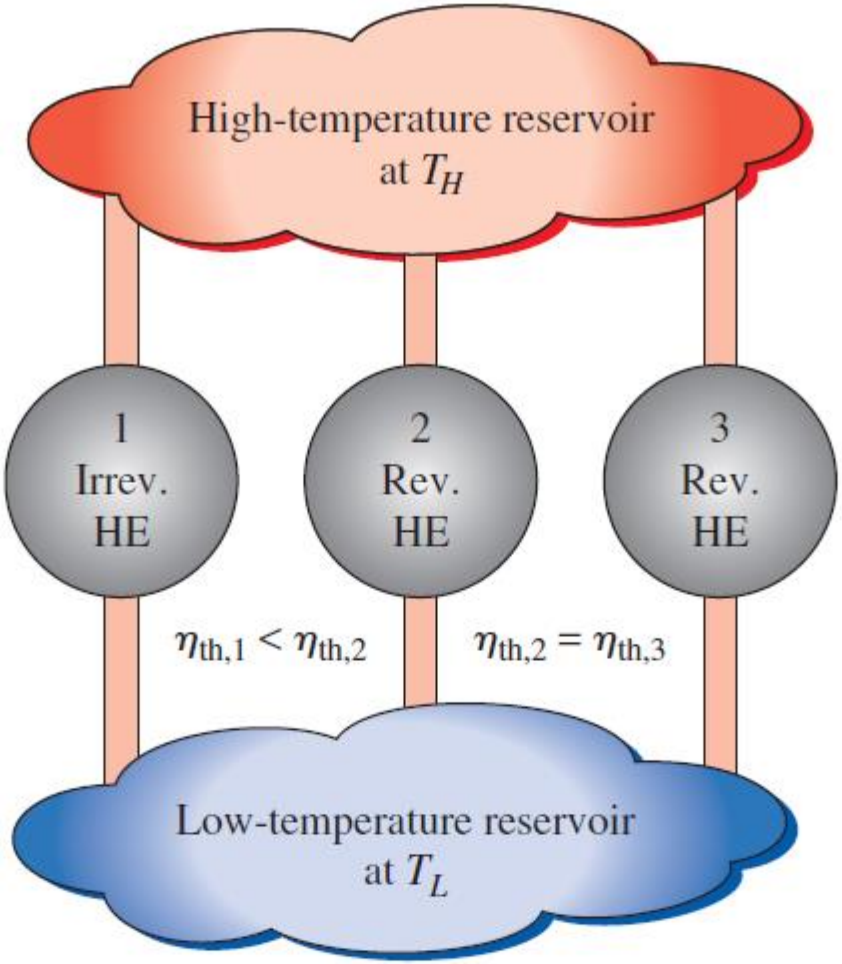
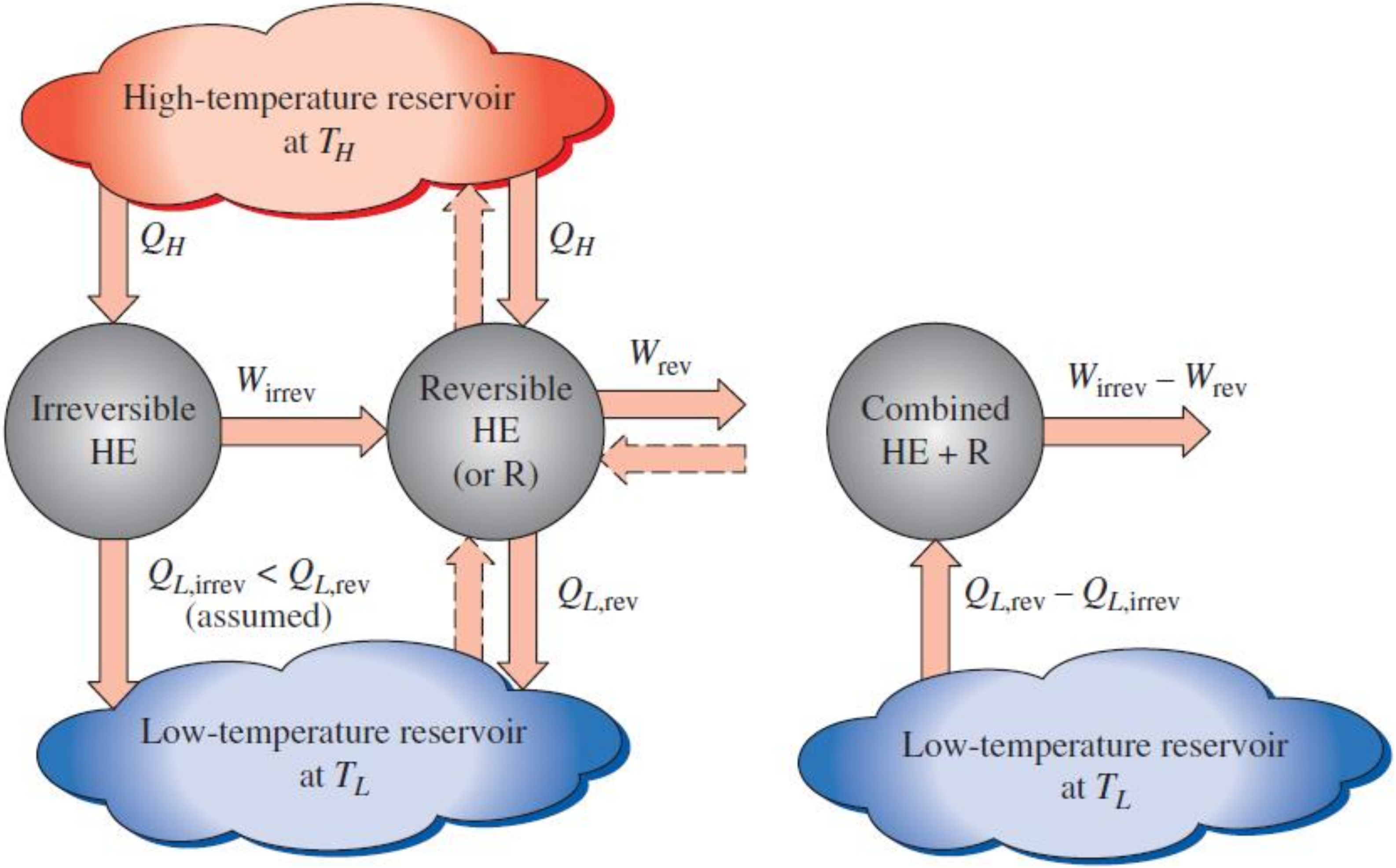


FIGURE 6–39
The Carnot principles.



(*a*) A reversible and an irreversible heat engine operating between the same two reservoirs (the reversible heat engine is then reversed to run as a refrigerator)

(*b*) The equivalent combined system

FIGURE 6–40

Proof of the first Carnot principle.

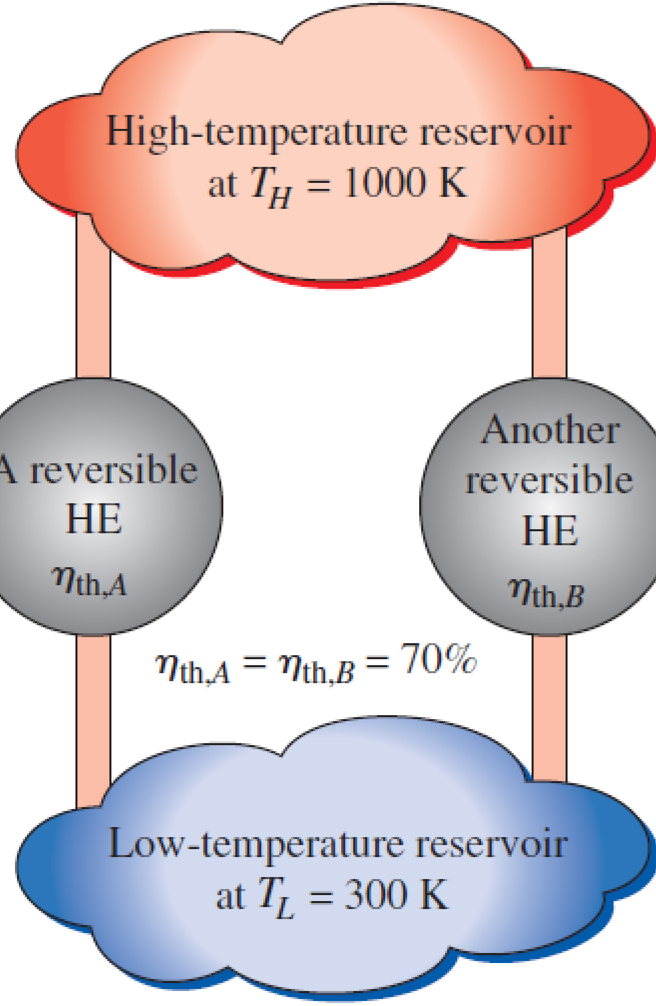


FIGURE 6–41

All reversible heat engines operating between the same two reservoirs have the same efficiency (the second Carnot principle).

THE THERMODYNAMIC TEMPERATURE SCALE

A temperature scale that is independent of the properties of the substances that are used to measure temperature is called a **thermodynamic temperature scale**.

Such a temperature scale offers great conveniences in thermodynamic calculations.

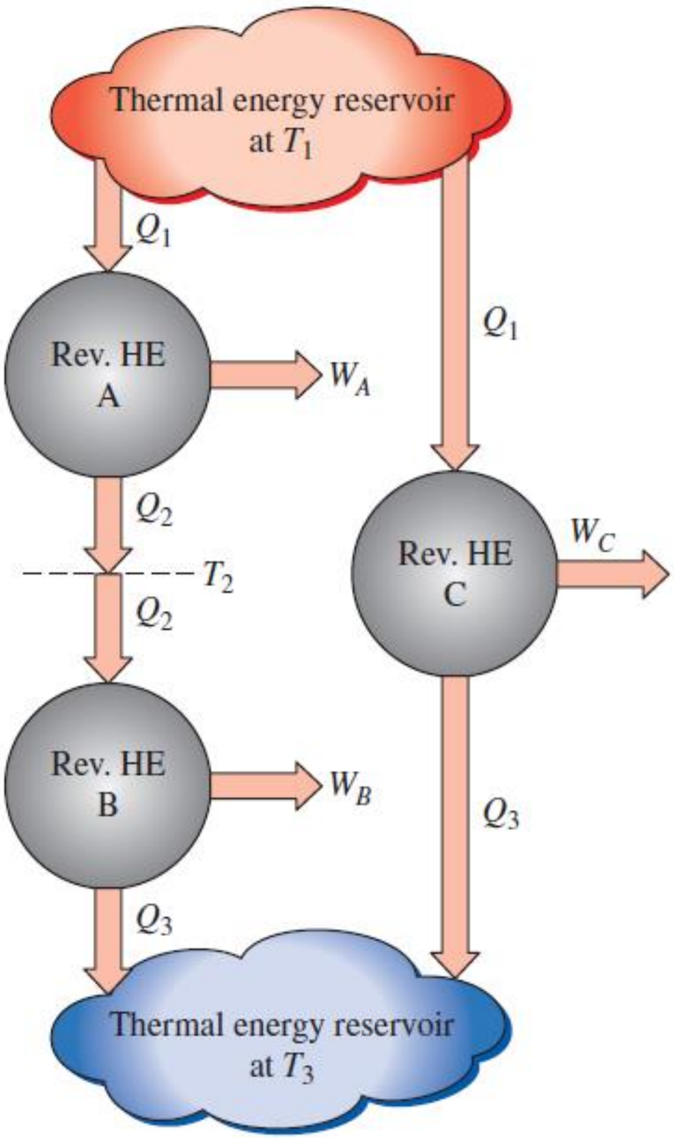


FIGURE 6–42

The arrangement of heat engines used to develop the thermodynamic temperature scale.

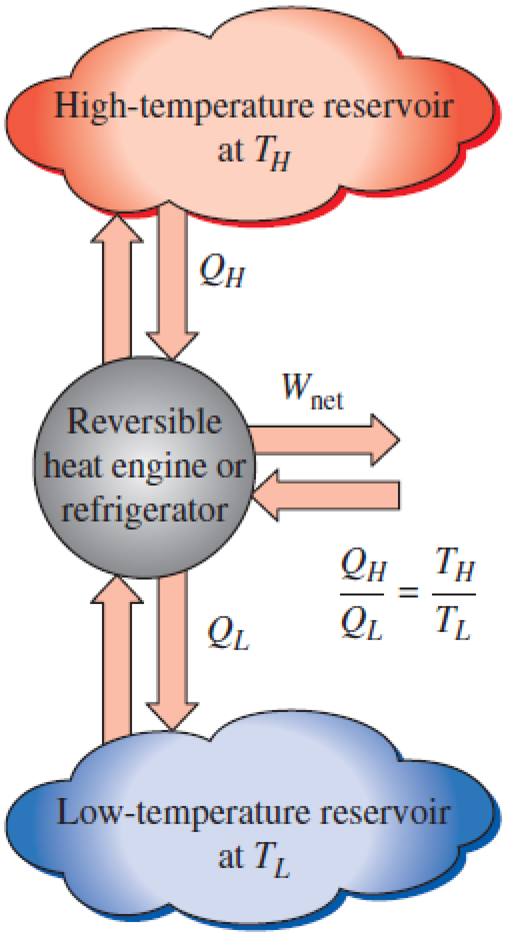


FIGURE 6–43
For reversible cycles, the heat transfer ratio Q_H/Q_L can be replaced by the absolute temperature ratio T_H/T_L.

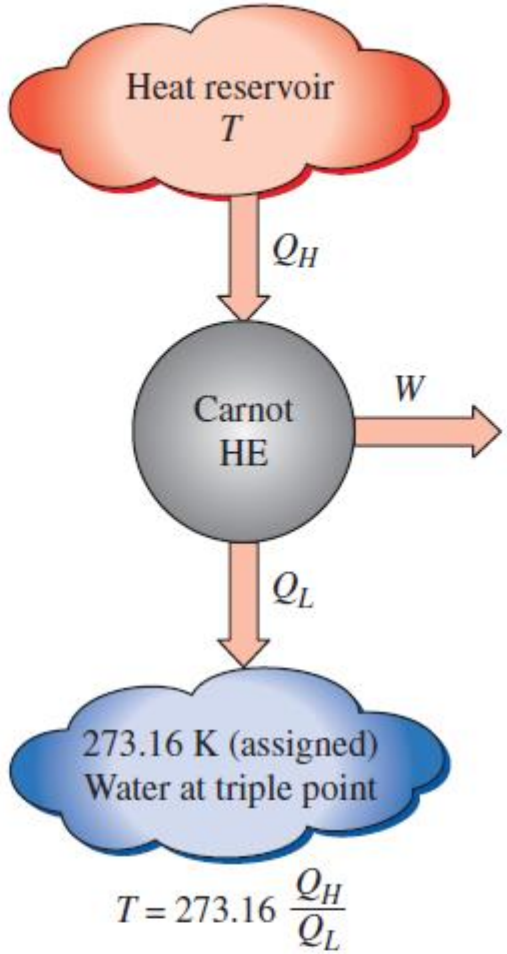


FIGURE 6–44
A conceptual experimental setup to determine thermodynamic temperatures on the Kelvin scale by measuring heat transfers Q_H and Q_L.

$$\left(\frac{Q_H}{Q_L}\right)_{\text{rev}} = \frac{T_H}{T_L}$$

This temperature scale is called the **Kelvin scale**, and the temperatures on this scale are called **absolute temperatures**.

$$T(^\circ\text{C}) = T(\text{K}) - 273.15$$

THE CARNOT HEAT ENGINE

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$ Any heat engine

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}$$ Carnot heat engine

$$\eta_{th} \begin{cases} < & \eta_{th,rev} \quad \text{irreversible heat engine} \\ = & \eta_{th,rev} \quad \text{reversible heat engine} \\ > & \eta_{th,rev} \quad \text{impossible heat engine} \end{cases}$$

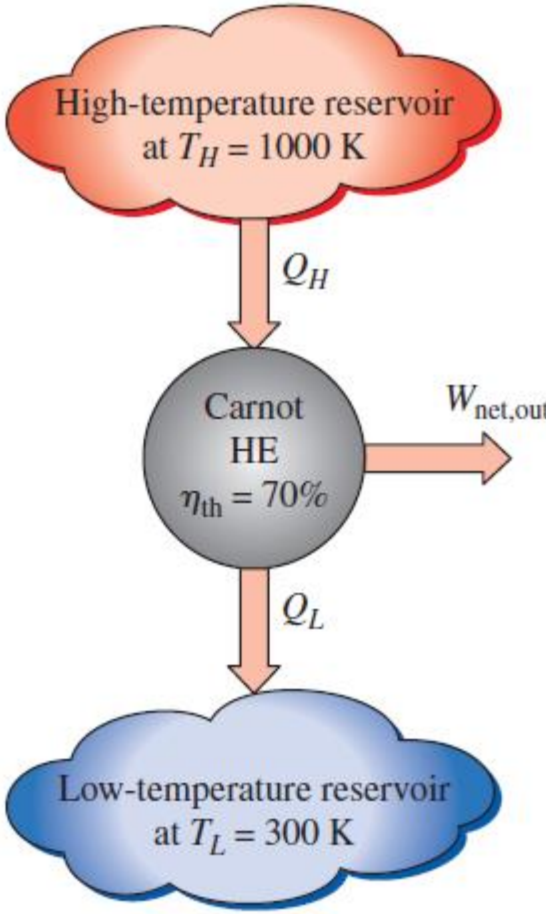


FIGURE 6–45
The Carnot heat engine is the most efficient of all heat engines operating between the same high- and low-temperature reservoirs.

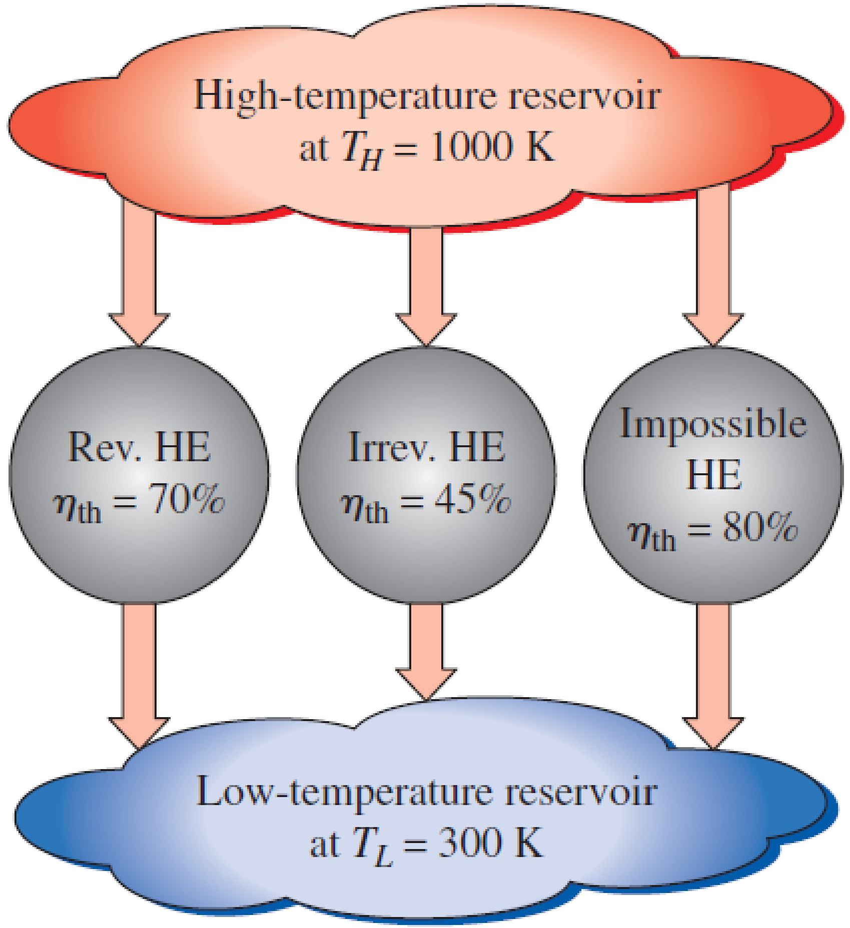
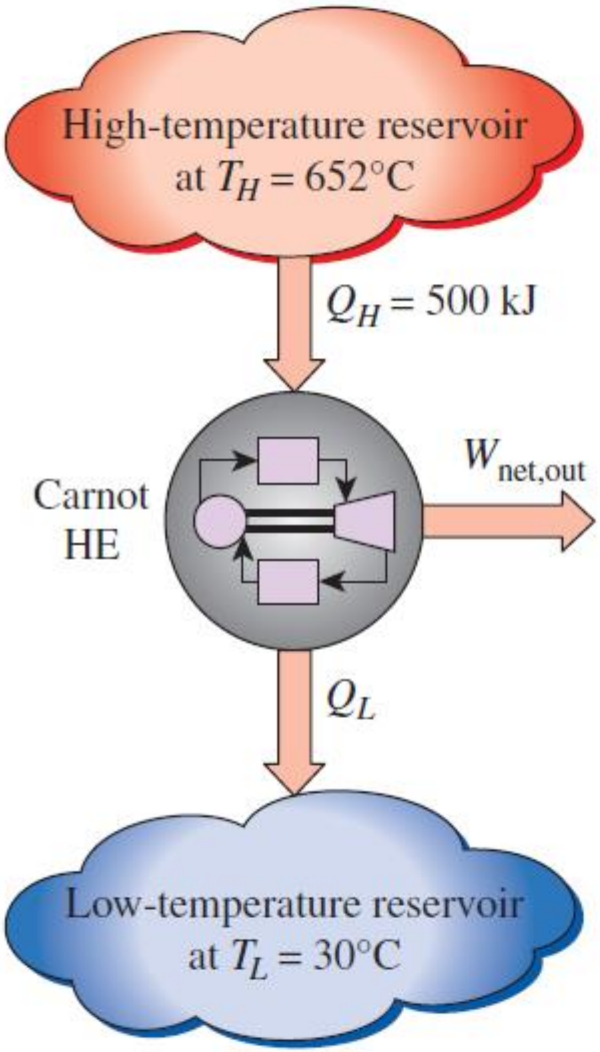


FIGURE 6–46

No heat engine can have a higher efficiency than a reversible heat engine operating between the same high- and low-temperature reservoirs.

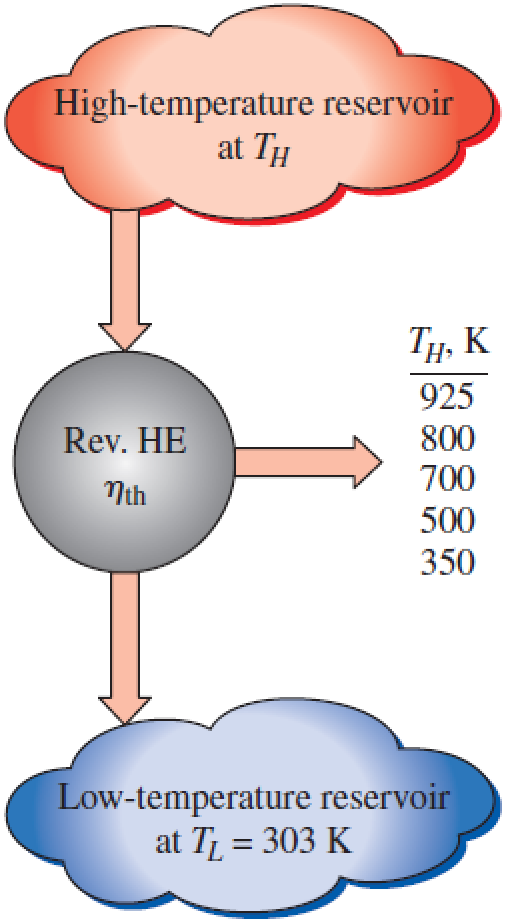
Analysis of a Carnot Heat Engine



A Carnot heat engine receives 500 kJ of heat per cycle from a high-temperature source at 652°C and rejects heat to a low temperature sink at 30°C. Determine the thermal efficiency of this Carnot engine and the amount of heat rejected to the sink per cycle.

Example 4

The Quality of Energy



T_H, K	η_{th}, %
925	67.2
800	62.1
700	56.7
500	39.4
350	13.4

FIGURE 6–48
The fraction of heat that can be converted to work as a function of source temperature (for T_L = 303 K).

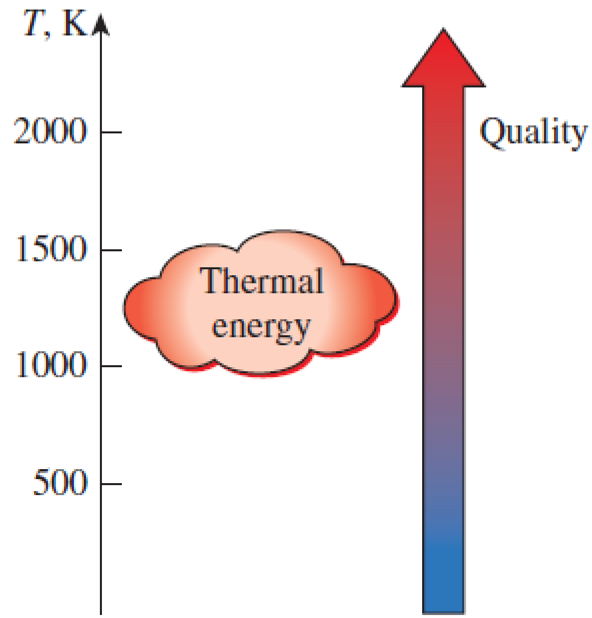


FIGURE 6–49
The higher the temperature of the thermal energy, the higher its quality.

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}$$

Can we use °C unit for temperature here?

How do you increase the thermal efficiency of a Carnot heat engine?

How about for actual heat engines?

THE CARNOT REFRIGERATOR AND HEAT PUMP

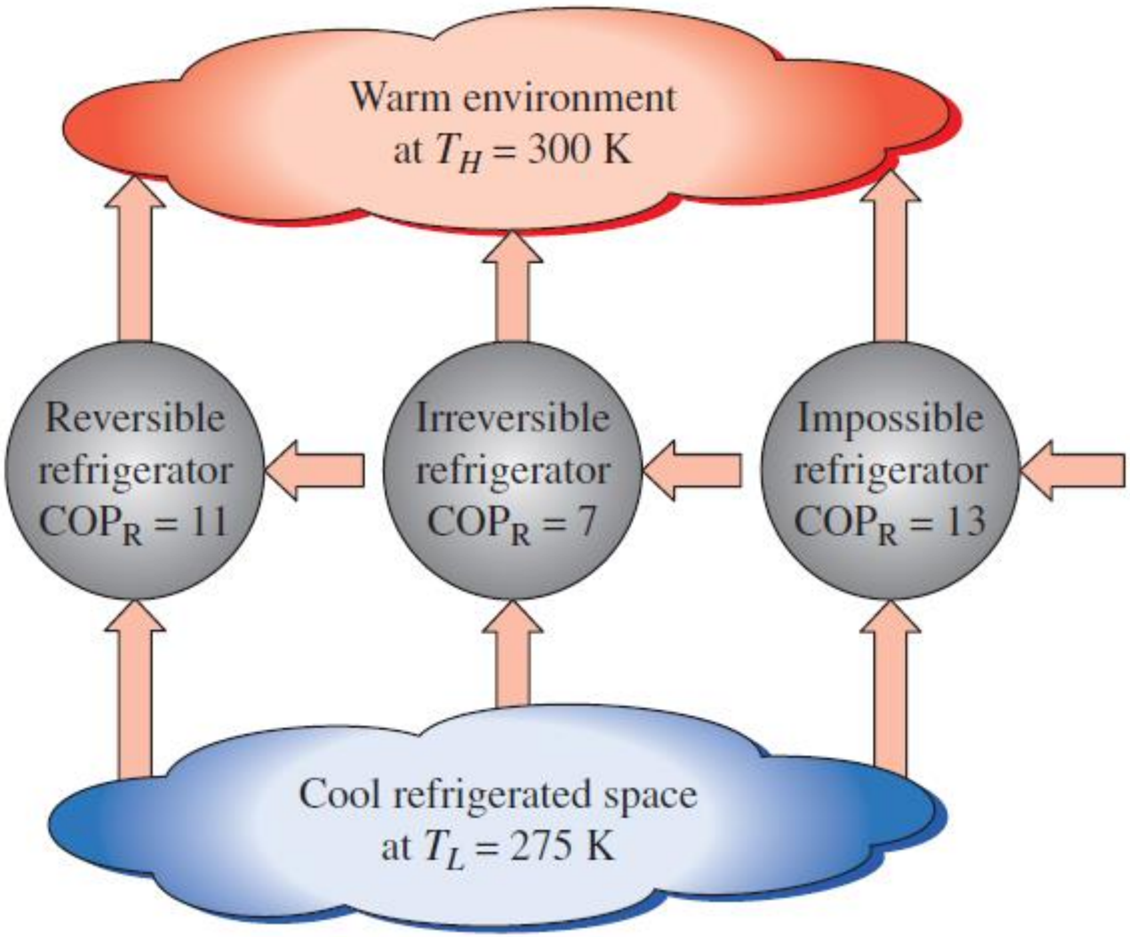


FIGURE 6–50

No refrigerator can have a higher COP than a reversible refrigerator operating between the same temperature limits.

Any refrigerator or heat pump

$$\mathrm{COP_R} = \frac{1}{Q_H/Q_L - 1}$$

$$\mathrm{COP_{HP}} = \frac{1}{1 - Q_L/Q_H}$$

Carnot refrigerator or heat pump

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

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

How do you increase the COP of a Carnot refrigerator or heat pump? How about for actual ones?

$$\mathrm{COP_R} \begin{cases} < \mathrm{COP_{R,rev}} & \text{irreversible refrigerator} \\ = \mathrm{COP_{R,rev}} & \text{reversible refrigerator} \\ > \mathrm{COP_{R,rev}} & \text{impossible refrigerator} \end{cases}$$

The COP of a reversible refrigerator or heat pump is the maximum theoretical value for the specified temperature limits.

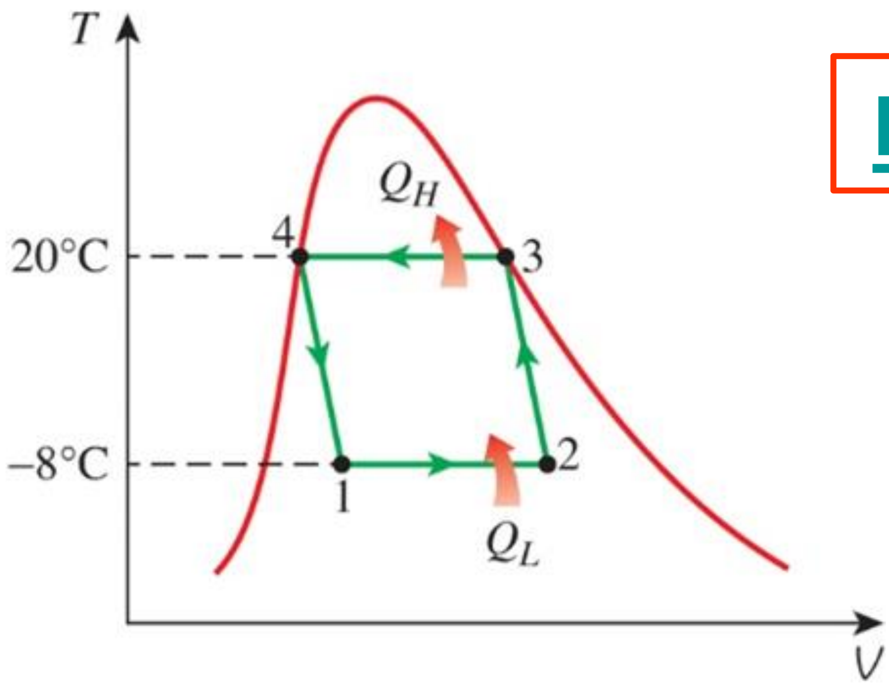
Actual refrigerators or heat pumps may approach these values as their designs are improved, but they can never reach them.

The COPs of both the refrigerators and the heat pumps <u>decrease</u> as T_L <u>decreases</u>.

That is, it requires more work to absorb heat from lower-temperature media.

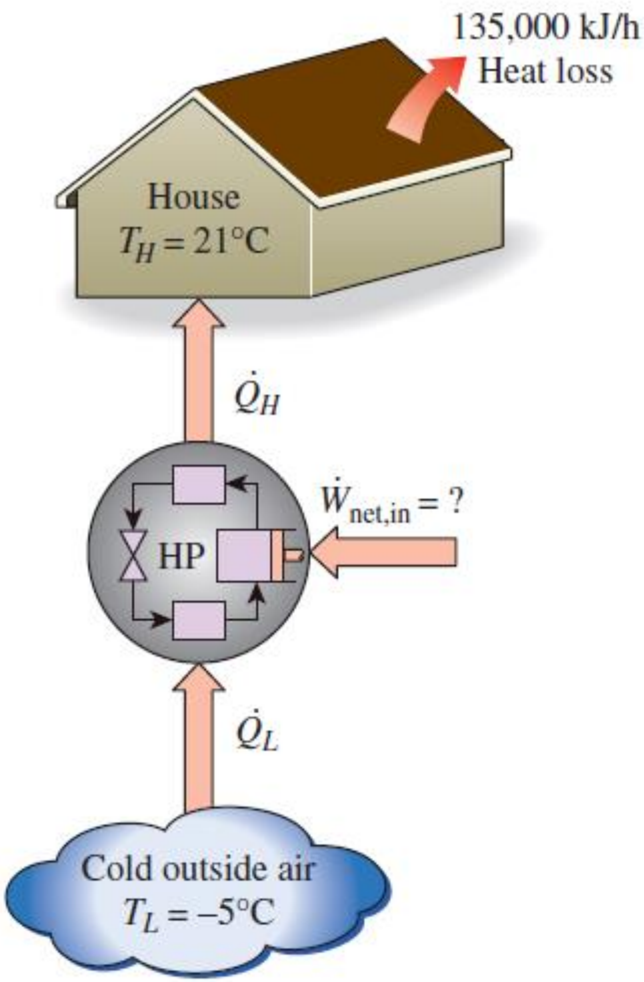
A Carnot Refrigerator Operating in the Saturation Dome

A Carnot refrigeration cycle is executed in a closed system in the saturated liquid-vapor mixture region using 0.8 kg of R-134a as the working fluid. The maximum and minimum temperatures in the cycle are 20 and -8^{o}C, respectively. It is known that the R-134a is a saturated liquid at the end of the heat rejection process, and the net work input to the cycle is 15 kJ. Determine the mass that vaporizes during the heat addition process and the pressure at the end of the heat rejection process.



Example 5

Heating a House by a Carnot Heat Pump



A heat pump is to be used to heat a house during the winter. The house is to be maintained at 21ºC. The house is estimated to lose heat at a rate of 135,000 kJ/hr when the outside temperature drops to -5ºC. Determine the minimum power required to drive this heat pump.

Example 6

Proving the Validity of a Refrigerator

During an experiment conducted in a room at 25°C, a lab assistant measures that a refrigerator that draws 2 kW of power has removed 30,000 kJ of heat over a 20 minute period from a refrigerated space maintained at -30°C. Determine the COP of the refrigerator and whether it is possible.

Example 7

Summary

- Introduction to the second law
- Thermal energy reservoirs
- Perpetual motion machines
- Reversible and irreversible processes
  - ✓ Irreversibilities, Internally and externally reversible processes
- The Carnot cycle
  - ✓ The reversed Carnot cycle
- The Carnot principles
- The thermodynamic temperature scale
- The Carnot heat engine
  - ✓ The quality of energy
- The Carnot refrigerator and heat pump