Thermodynamics: An Engineering Approach
8th Edition
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Topic 11
Heat Engines

Objectives

- Discuss heat engines, refrigerators, and heat pumps.
- Describe the Kelvin–Planck and Clausius statements of the second law of thermodynamics.

HEAT ENGINES

HEAT ENGINES: The devices that **convert heat to work**.

1. They receive heat from a high-temperature source (solar energy, oil furnace, nuclear reactor, etc.).
2. They convert part of this heat to work (usually in the form of a rotating shaft.)
3. They reject the remaining waste heat to a low-temperature sink (the atmosphere, rivers, etc.).
4. They operate on a **cycle**.

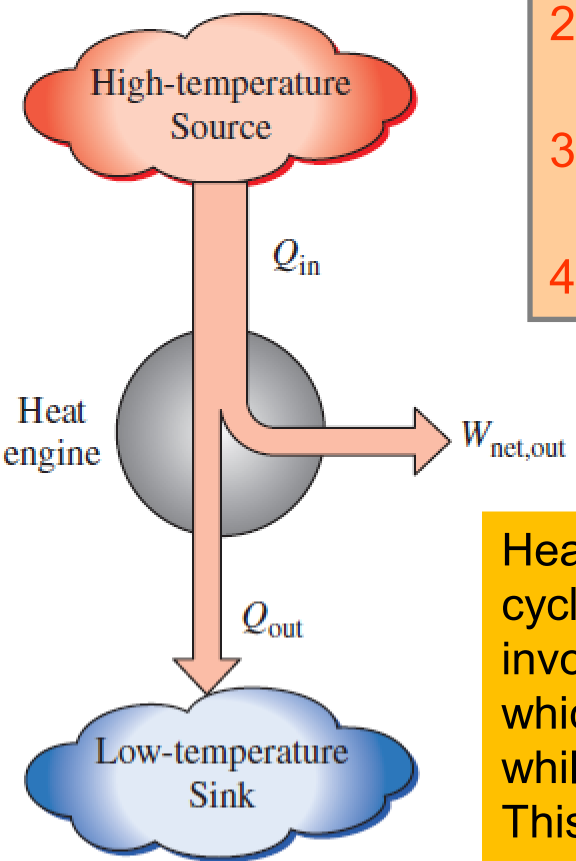


FIGURE 6–9
Part of the heat received by a heat engine is converted to work, while the rest is rejected to a sink.

Heat engines and other cyclic devices usually involve a fluid to and from which heat is transferred while undergoing a cycle. This fluid is called the **working fluid**.

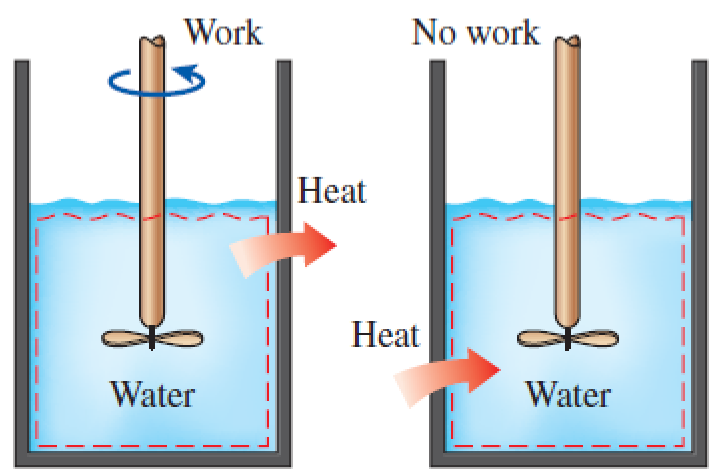
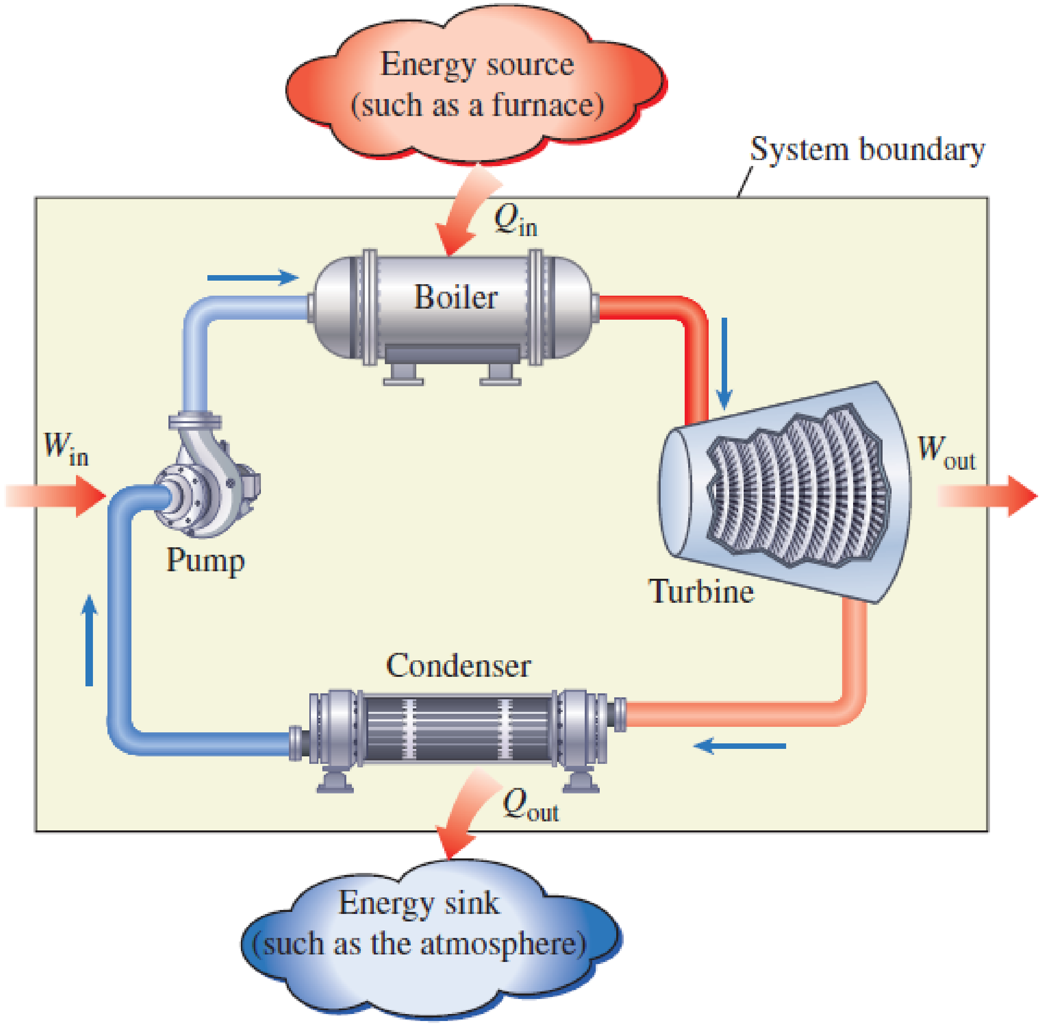


FIGURE 6–8
Work can always be converted to heat directly and completely, but the reverse is not true.

A steam power plant



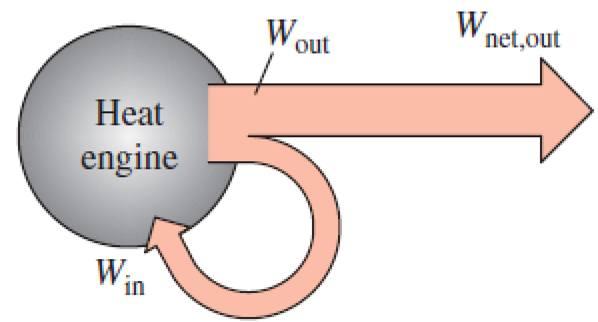


FIGURE 6–11

A portion of the work output of a heat engine is consumed internally to maintain continuous operation.

$$W_{net,out} = W_{out} - W_{in} \qquad (kJ)$$

$$W_{net,out} = Q_{in} - Q_{out} \qquad (kJ)$$

Q_{in} = amount of heat supplied to steam in boiler from a high-temperature source (furnace)

Q_{out} = amount of heat rejected from steam in condenser to a low-temperature sink (the atmosphere, a river, etc.)

W_{out} = amount of work delivered by steam as it expands in turbine

W_{in} = amount of work required to compress water to boiler pressure

Thermal efficiency

$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}}$$

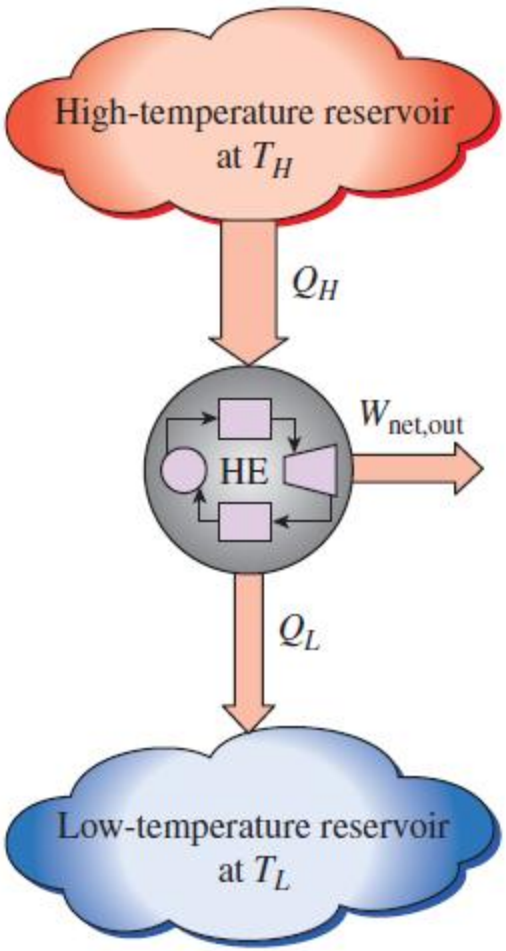


FIGURE 6–13
Schematic of a heat engine.

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}}$$

$$W_{net,out} = Q_{in} - Q_{out}$$

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}}$$

$$W_{net,out} = Q_H - Q_L$$

$$\eta_{th} = \frac{W_{net,out}}{Q_H}$$

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

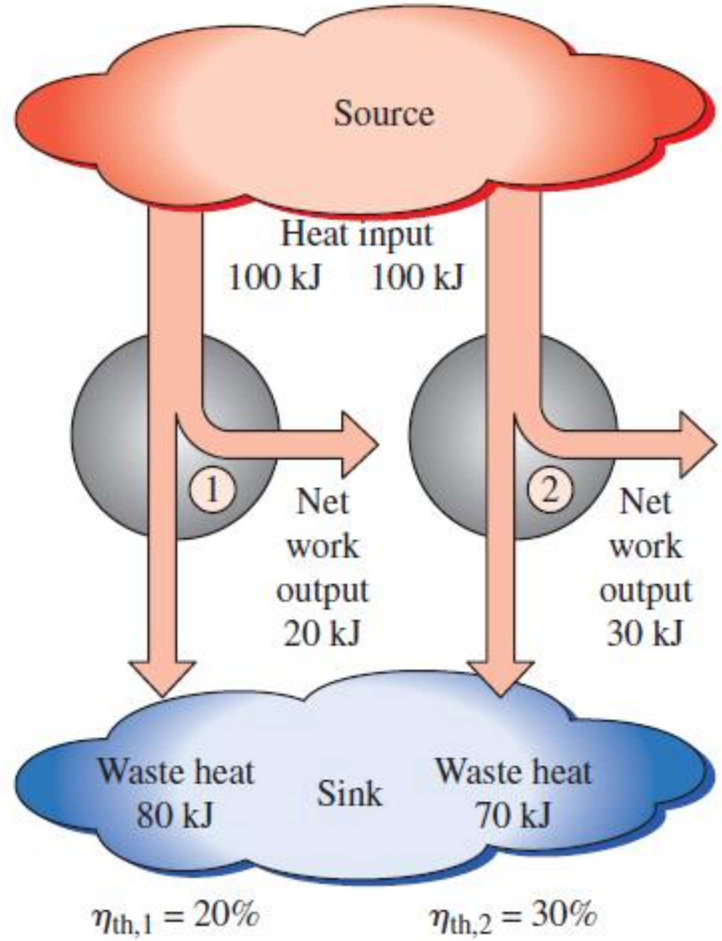


FIGURE 6–12
Some heat engines perform better than others (convert more of the heat they receive to work).

$$W_{\text{net,out}} = Q_H - Q_L$$

$$\eta_{\text{th}} = \frac{W_{\text{net,out}}}{Q_H} \quad \text{or} \quad \eta_{\text{th}} = 1 - \frac{Q_L}{Q_H}$$

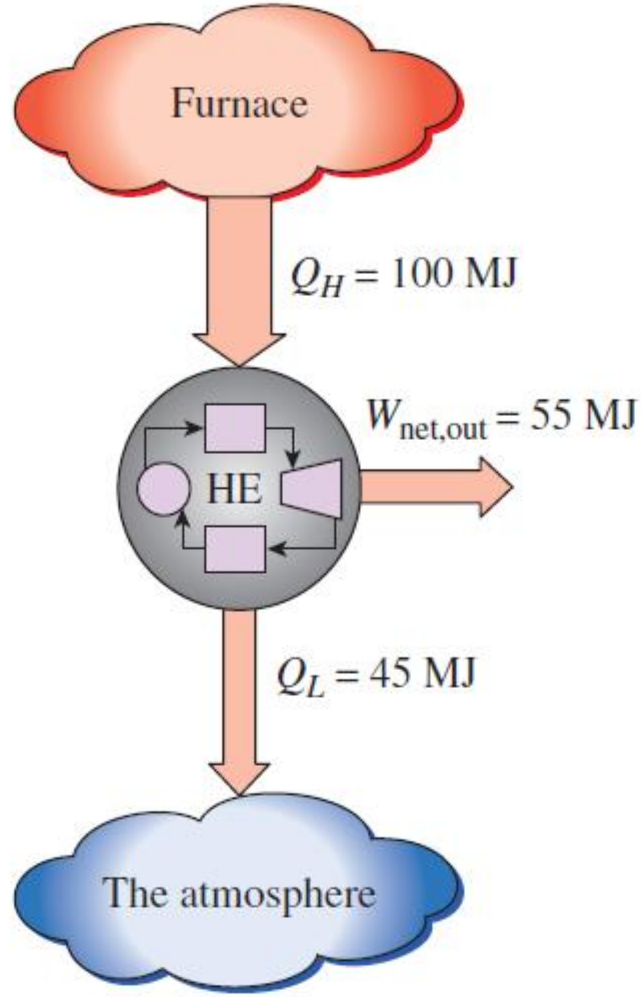


FIGURE 6–14

Even the most efficient heat engines reject almost one-half of the energy they receive as waste heat.

Can we save Q_{out}?

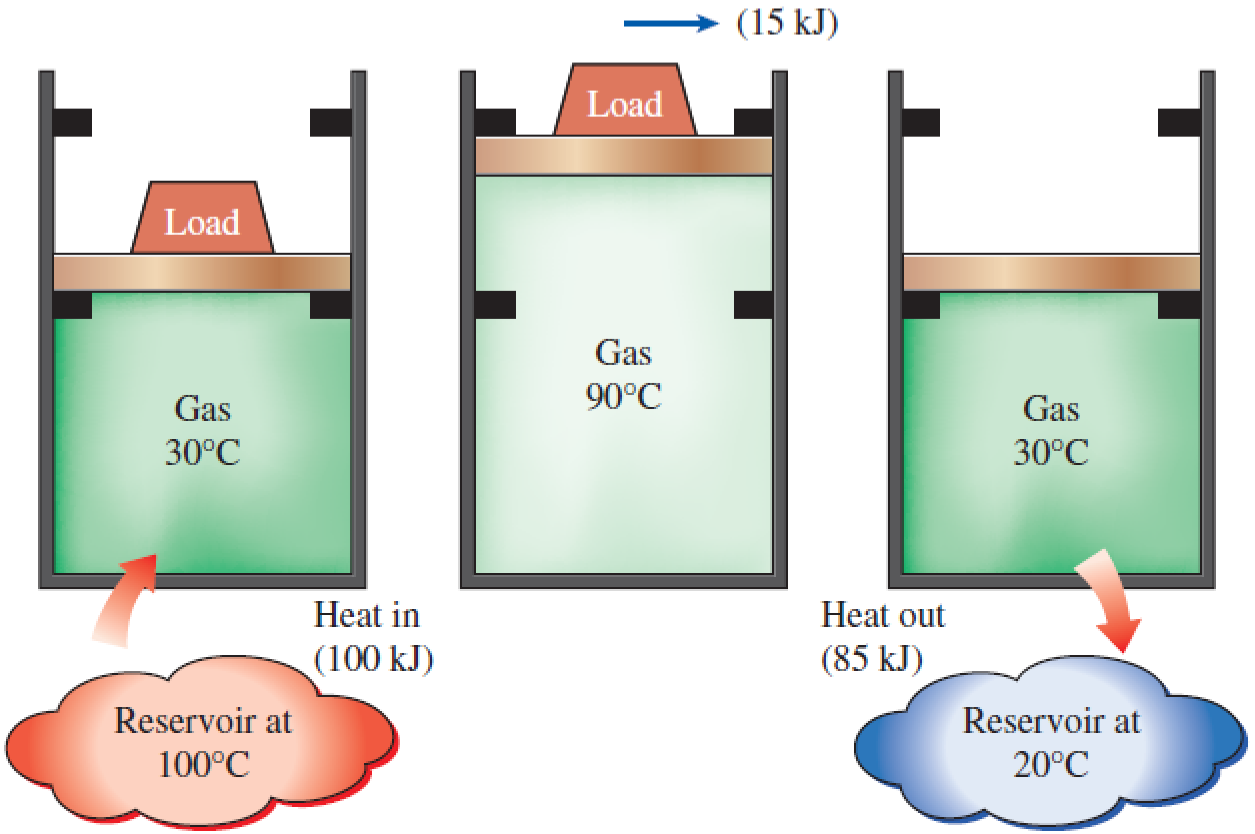


FIGURE 6–15
A heat-engine cycle cannot be completed without rejecting some heat to a low-temperature sink.

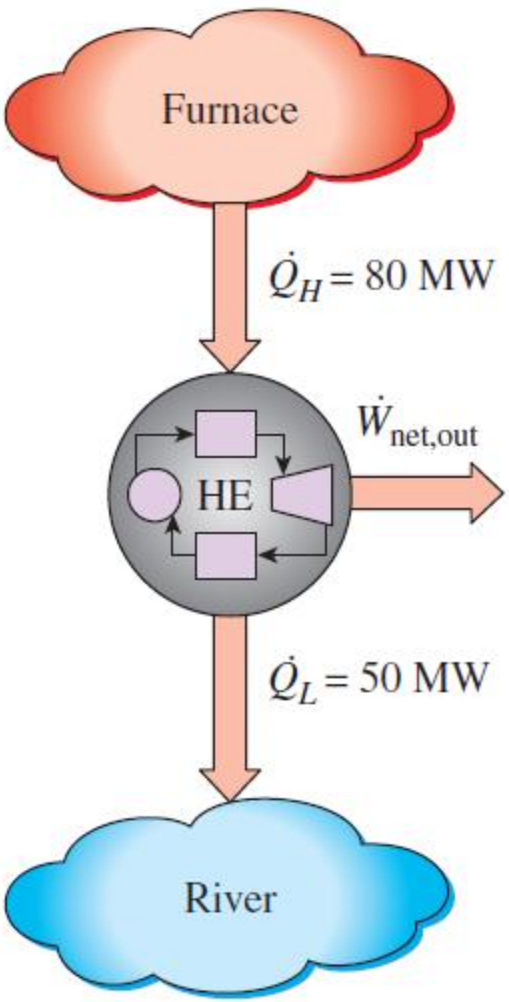
Every heat engine must *waste some energy* by transferring it to a low-temperature reservoir in order to complete the cycle, even under idealized conditions.

In a steam power plant, the condenser is the device where large quantities of waste heat is rejected to rivers, lakes, or the atmosphere.

Can we not just take the condenser out of the plant and save all that waste energy?

The answer is, unfortunately, a firm ***no*** for the simple reason that without a heat rejection process in a condenser, the cycle cannot be completed.

Net Power Production of a Heat Engine

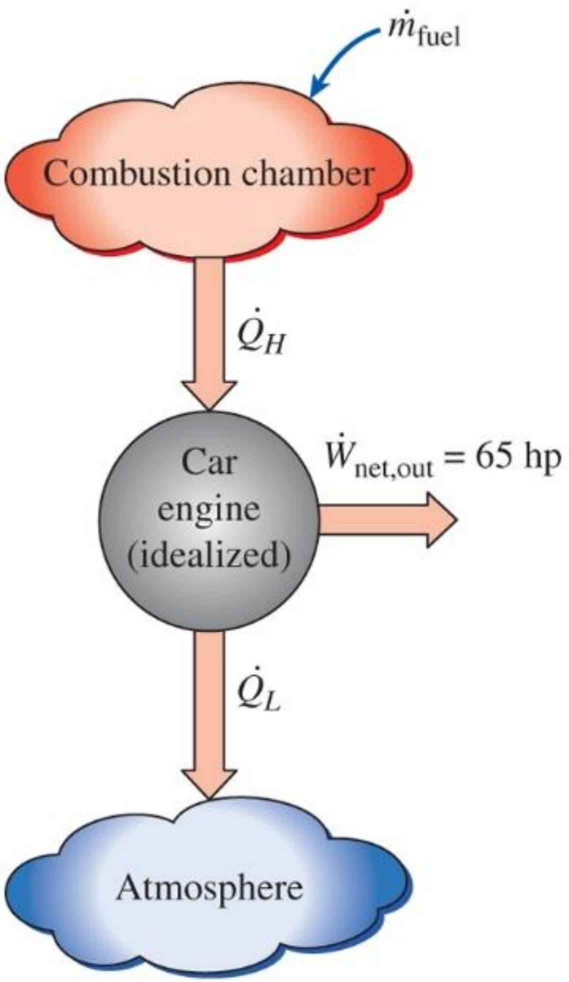


Heat is transferred to a heat engine from a furnace at a rate of 80 MW. If the rate of waste heat rejection to a nearby river is 50 MW, determine the net power output and the thermal efficiency for this heat engine.

Solution

Fuel Consumption Rate of a Car

A car engine with a power output of 65 hp has a thermal efficiency of 24%. Determine the fuel consumption rate of this car if the fuel has a heating value of 19,000 Btu/lbm. (2545 Btu/hr = 1hp)



Solution

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.

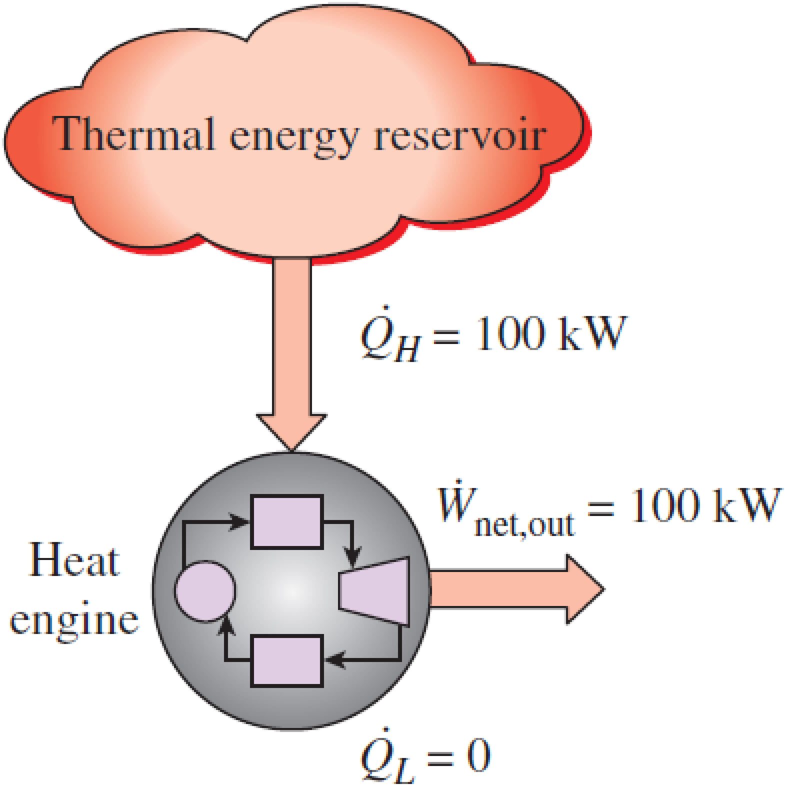


FIGURE 6–18
A heat engine that violates the Kelvin–Planck statement of the second law.

REFRIGERATORS AND HEAT PUMPS

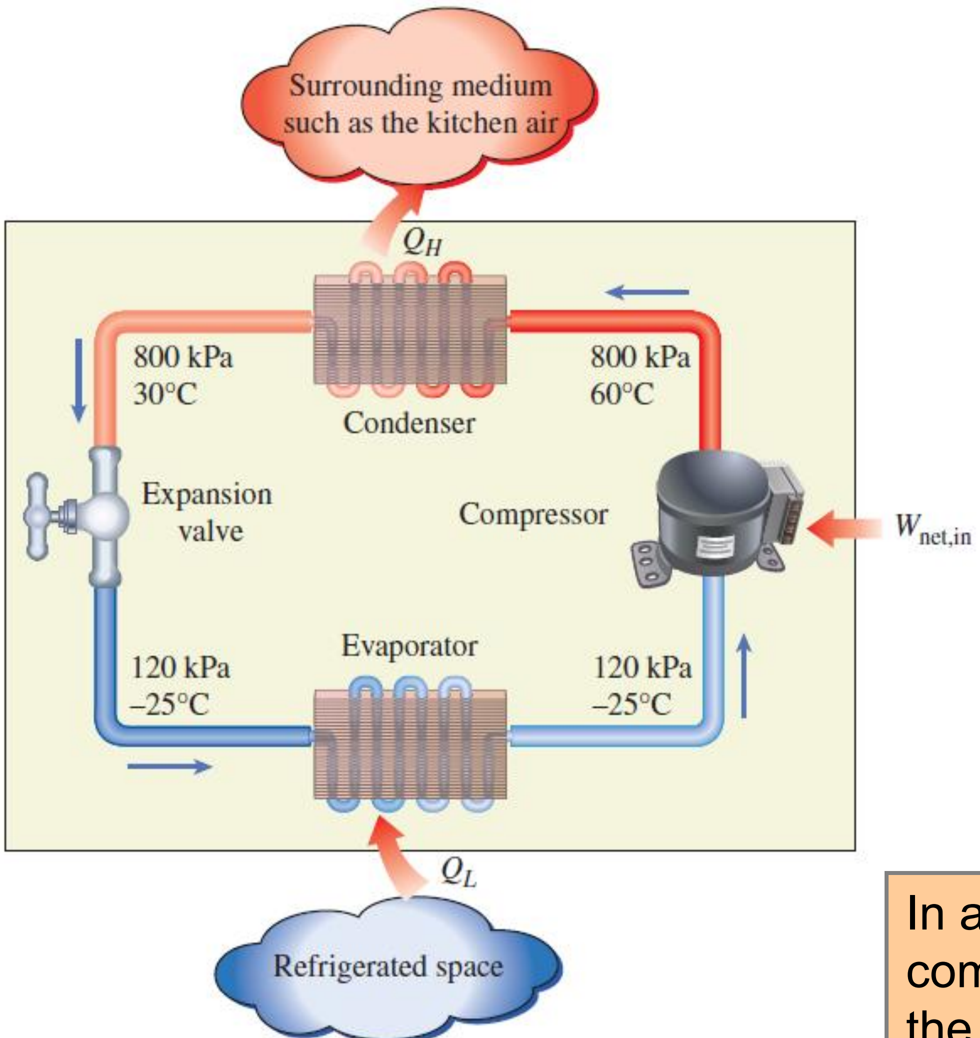


FIGURE 6–19
Basic components of a refrigeration system and typical operating conditions.

- The transfer of heat from a low-temperature medium to a high-temperature one requires special devices called **refrigerators**.
- Refrigerators, like heat engines, are cyclic devices.
- The working fluid used in the refrigeration cycle is called a **refrigerant**.
- The most frequently used refrigeration cycle is the ***vapor-compression refrigeration cycle***.

In a household refrigerator, the freezer compartment where heat is absorbed by the refrigerant serves as the evaporator, and the coils usually behind the refrigerator where heat is dissipated to the kitchen air serve as the condenser.

Coefficient of Performance

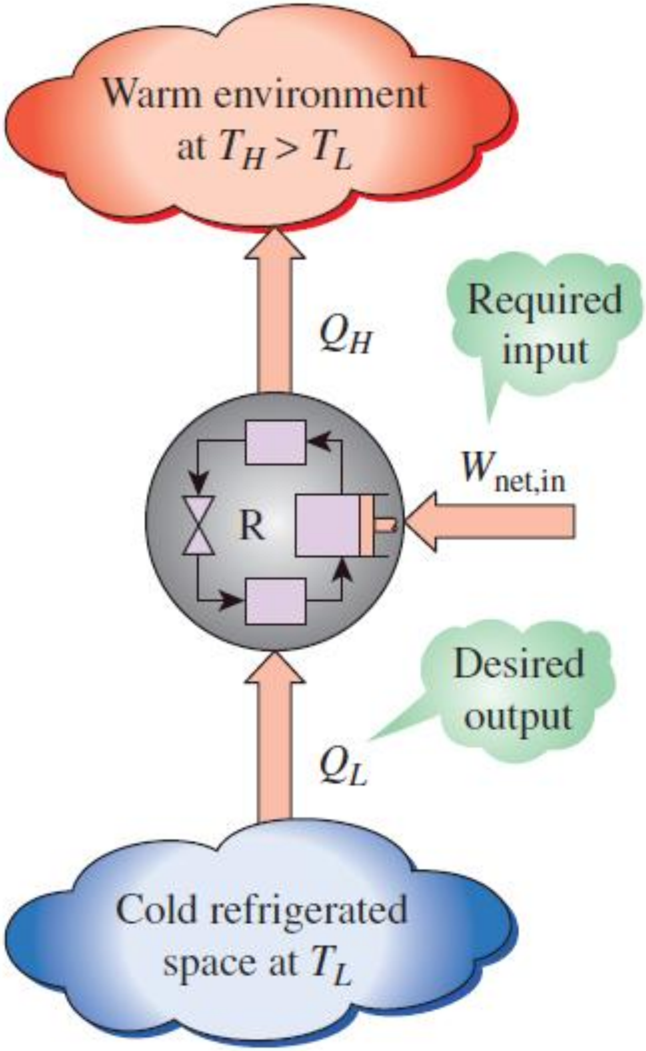


FIGURE 6–20
The objective of a refrigerator is to remove Q_L from the cooled space.

The *efficiency* of a refrigerator is expressed in terms of the **coefficient of performance (COP)**.

The objective of a refrigerator is to remove heat (Q_L) from the refrigerated space.

$$\text{COP}_\text{R} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{\text{net,in}}}$$

$$W_{\text{net,in}} = Q_H - Q_L \qquad \text{(kJ)}$$

$$\text{COP}_\text{R} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1}$$

Can the value of COP_R be greater than unity?

Heat Pumps

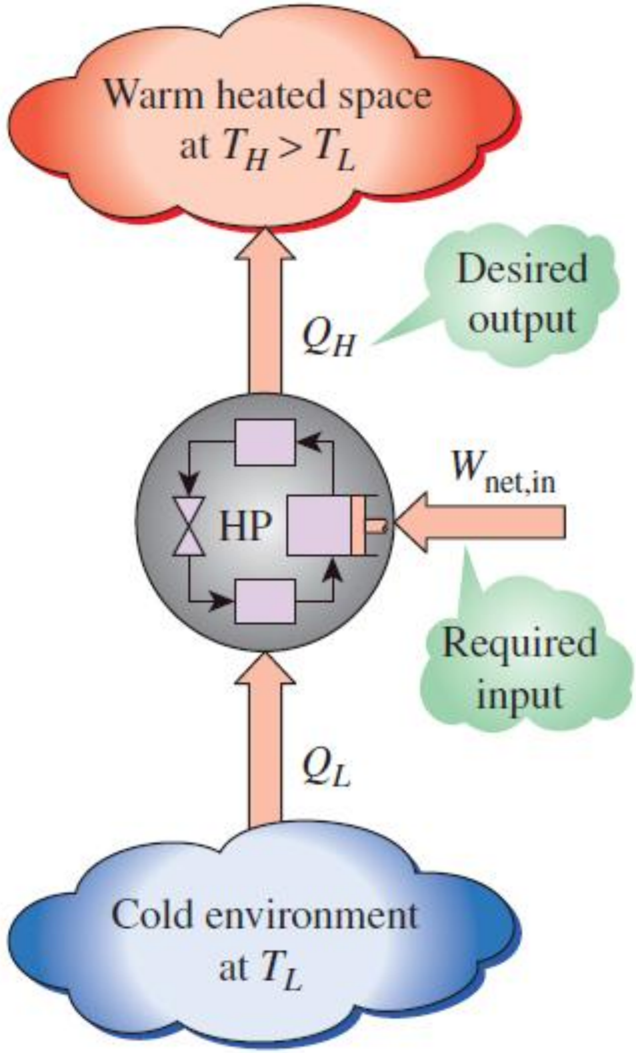


FIGURE 6–21

The objective of a heat pump is to supply heat Q_H into the warmer space.

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

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

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

for fixed values of Q_L and Q_H

Can the value of $\mathrm{COP_{HP}}$ be lower than unity?

What does $\mathrm{COP_{HP}}$=1 represent?

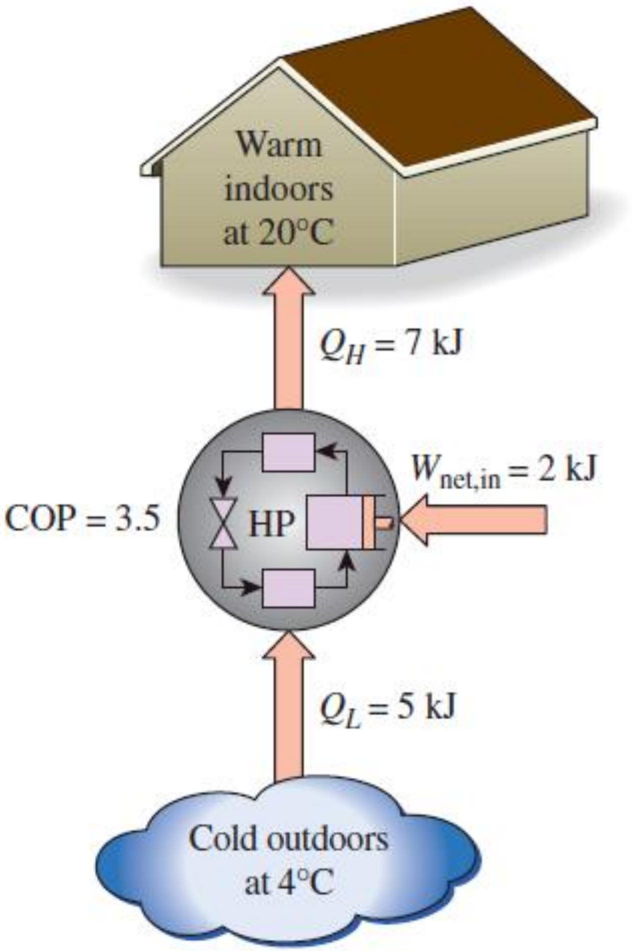


FIGURE 6–22

The work supplied to a heat pump is used to extract energy from the cold outdoors and carry it into the warm indoors.

- Most heat pumps in operation today have a seasonally averaged COP of 2 to 3.
- Most existing heat pumps use the cold outside air as the heat source in winter (*air-source* HP).
- In cold climates their efficiency drops considerably when temperatures are below the freezing point.
- In such cases, *geothermal* (*ground-source*) HP that use the ground as the heat source can be used.
- Such heat pumps are more expensive to install, but they are also more efficient.
- **Air conditioners** are basically refrigerators whose refrigerated space is a room or a building instead of the food compartment.
- The COP of a refrigerator decreases with decreasing refrigeration temperature.
- Therefore, it is not economical to refrigerate to a lower temperature than needed.

Energy efficiency rating (EER): The amount of heat removed from the cooled space in Btu's for 1 Wh (watthour) of electricity consumed.

$$EER \equiv 3.412\ COP_R$$

Heat Rejection by a Refrigerator

The food compartment of a refrigerator is maintained at 4^{o}C by removing heat from it at a rate of 360 kJ/min. If the required power input to the refrigerator is 2 kW, determine the coefficient of performance of the refrigerator and the rate of heat rejection to the room that houses the refrigerator.

Solution

Heating a House by a Heat Pump

A heat pump is used to meet the heating requirements of a house and maintain it at 20^{o}C. On a day when the outdoor air temperature drops to -2^{o}C, the house is estimated to lose heat at a rate of 80,000 kJ/hr. If the heat pump under these conditions has a COP of 2.5, determine the power consumed by the heat pump and the rate at which heat is absorbed from the cold outdoor air.

Solution

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 cannot operate unless its compressor is driven by an external power 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.

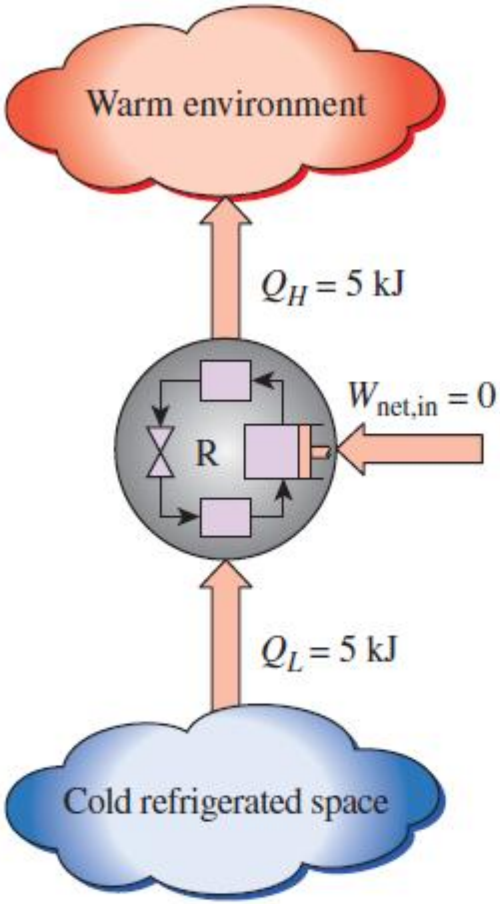
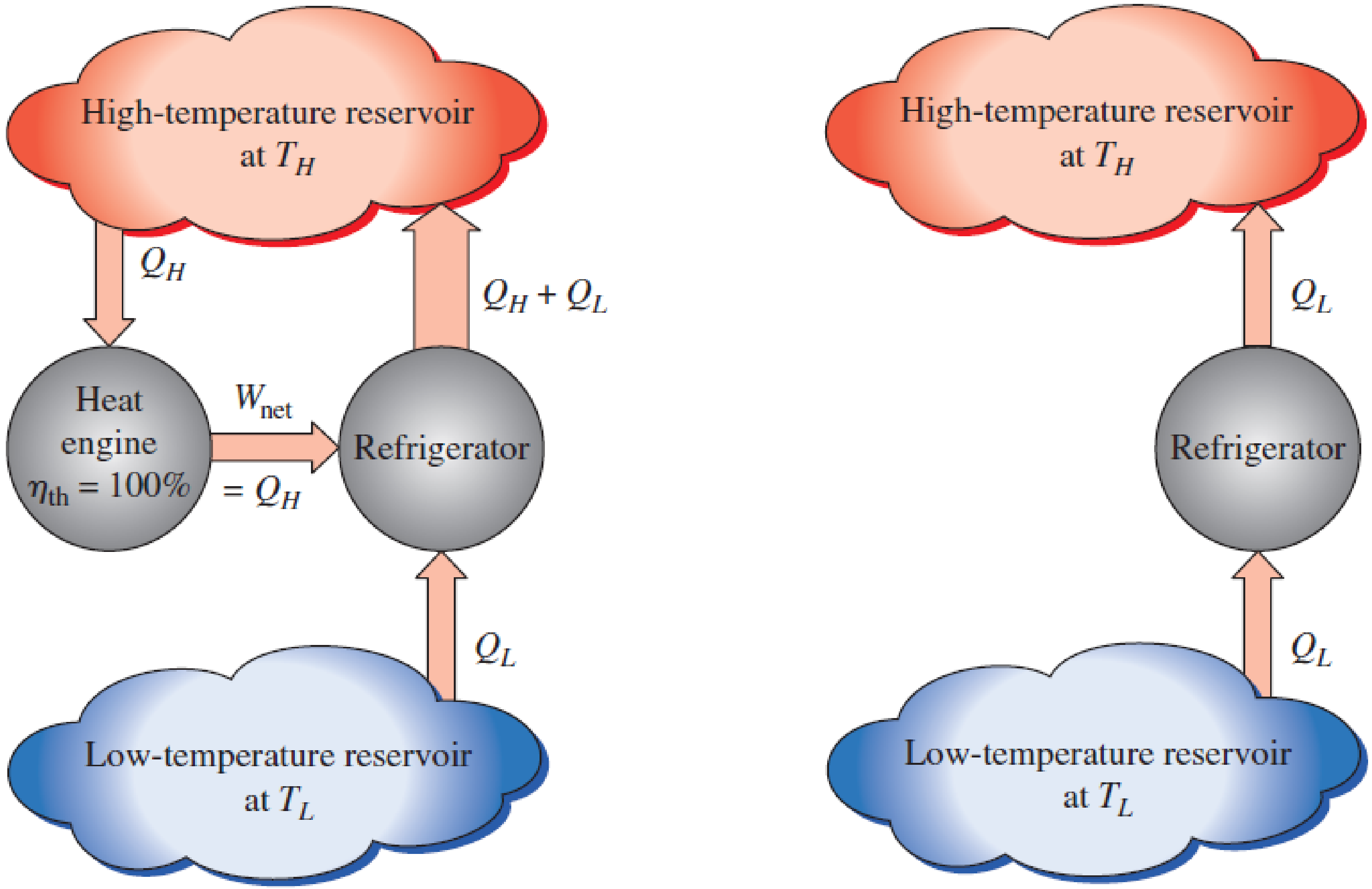


FIGURE 6–25
A refrigerator that violates the Clausius statement of the second law.

Equivalence of the Two Statements



(*a*) A refrigerator that is powered by a 100 percent efficient heat engine

(*b*) The equivalent refrigerator

Proof that the violation of the Kelvin–Planck statement leads to the violation of the Clausius statement.

The Kelvin–Planck and the Clausius statements are equivalent in their consequences, and either statement can be used as the expression of the second law of thermodynamics.

Any device that violates the Kelvin–Planck statement also violates the Clausius statement, and vice versa.

Summary

- Heat engines
  - ✓ Thermal efficiency
  - ✓ The 2nd law: Kelvin-Planck statement
- Refrigerators and heat pumps
  - ✓ Coefficient of performance (COP)
  - ✓ The 2nd law: Clausius statement