Thermodynamics: An Engineering Approach

Chapter 6

THE SECOND LAW OF THERMODYNAMICS

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- To this point, we have focused our attention on the first law of thermodynamics, which requires that energy be conserved during a process.
- In this chapter, we introduce **the second law of thermodynamics**, which asserts that processes occur in a certain direction and that energy has quality as well as quantity.
- A process cannot take place unless it satisfies both the first and second laws of thermodynamics.
- In this chapter, **the thermal energy reservoirs, reversible and irreversible processes, heat engines, refrigerators, and heat pumps are introduced first.**
- The Carnot cycle is introduced next, and the Carnot principles are discussed.
- Finally, the idealized Carnot heat engines, refrigerators, and heat pumps are examined.

Objectives

The objectives of Chapter 5 are to:

- Introduce the second law of thermodynamics.
- Identify valid processes as those that satisfy both the first and second laws of thermodynamics.
- Discuss thermal energy reservoirs, reversible and irreversible processes, heat engines, refrigerators, and heat pumps.
- Describe the Kelvin–Planck and Clausius statements of the second law of thermodynamics.
- Apply the second law of thermodynamics to cycles and cyclic devices.
- Describe the Carnot cycle.

Objectives

- 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

- In Chaps. 4 and 5, we applied the *first law of thermodynamics*, or the *conservation of energy principle*, to processes involving closed and open systems.

- As pointed out repeatedly in those chapters, energy is a conserved property, and no process is known to have taken place in violation of the first law of thermodynamics.

- Therefore, it is reasonable to conclude that a process must satisfy the first law to occur. However, as explained here, **satisfying the first law alone does not ensure that the process will actually take place.**

- It is common experience that a cup of hot coffee left in a cooler room eventually cools off (Fig. 6–1). This process satisfies the first law of thermodynamics since the amount of energy lost by the coffee is equal to the amount gained by the surrounding air.

- Now let us consider the reverse process—the hot coffee getting even hotter in a cooler room as a result of heat transfer from the room air. We all know that this process never takes place. Yet, doing so would not violate the first law as long as the amount of energy lost by the air is equal to the amount gained by the coffee.

- **As another familiar example, consider the heating of a room by the passage of electric current through a resistor (Fig. 6–2).**
- **Again, the first law dictates that the amount of electric energy supplied to the resistance wires be equal to the amount of energy transferred to the room air as heat.**
- **Now let us attempt to reverse this process. It will come as no surprise that transferring some heat to the wires does not cause an equivalent amount of electric energy to be generated in the wires.**
- **Finally, consider a paddle-wheel mechanism that is operated by the fall of a mass (Fig. 6–3).**
- The paddle wheel rotates as the mass falls and stirs a fluid within an insulated container.
- As a result, the potential energy of the mass decreases, and the internal energy of the fluid increases in accordance with the conservation of energy principle. However, the reverse process, raising the mass by transferring heat from the fluid to the paddle wheel, does not occur in nature, although doing so would not violate the first law of thermodynamics.

- **It is clear from these arguments that processes proceed in a *certain direction* and not in the reverse direction (Fig. 6–4).**

- **The first law places no restriction on the direction of a process, but satisfying the first law does not ensure that the process can actually occur.**

- This inadequacy of the **first law to identify whether a process can take place is remedied by introducing another general principle, the *second law of thermodynamics*.** We show later in this chapter that the reverse processes discussed above violate the second law of thermodynamics.

- **A process cannot occur unless it satisfies both the first and the second laws of thermodynamics (Fig. 6–5).**

- There are numerous valid statements of the second law of thermodynamics. Two such statements are presented and discussed later in this chapter in relation to some engineering devices that operate on cycles.

- The use of **the second law of thermodynamics** is not limited to identifying the **direction of processes**, however. 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.**

- **Preserving the quality of energy is a major concern to engineers, and the second law provides the necessary means to determine the quality as well as the degree of degradation of energy during a process.**

- **As discussed later in this chapter, more of high-temperature energy can be converted to work, and thus it has a higher quality than the same amount of energy at a lower temperature.**

- **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 6–1

A cup of hot coffee does not get hotter in a cooler room.

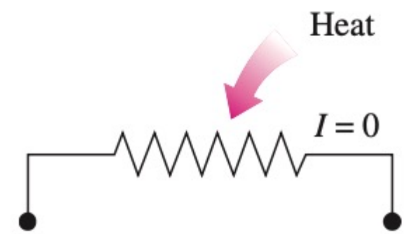


FIGURE 6–2

Transferring heat to a wire will not generate electricity.

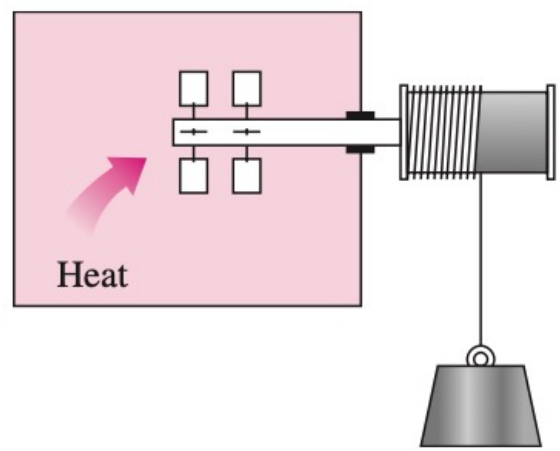


FIGURE 6–3

Transferring heat to a paddle wheel will not cause it to rotate.

FIGURE 6–4

Processes occur in a certain direction, and not in the reverse direction.

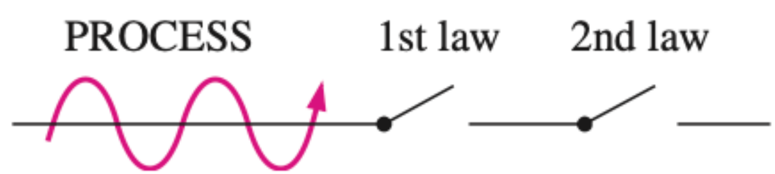


FIGURE 6–5

A process must satisfy both the first and second laws of thermodynamics to proceed.

THERMAL ENERGY RESERVOIRS

- In the development of the second law of thermodynamics, it is very convenient to have a **hypothetical body with a relatively large *thermal energy capacity* (mass × specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature.**

- Such a body 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 (Fig. 6–6).

- **The *atmosphere*, for example, does not warm up as a result of heat losses from residential buildings in winter. Likewise, megajoules of waste energy dumped in large rivers by power plants do not cause any significant change in water temperature.**

- A *two-phase system* can be modeled as a reservoir also since it can absorb and release large quantities of heat while remaining at constant temperature.

- **Another familiar example of a thermal energy reservoir is the *industrial furnace*. The temperatures of most furnaces are carefully controlled, and they are capable of supplying large quantities of thermal energy as heat in an essentially isothermal manner. Therefore, they can be modeled as reservoirs.**

- A body does not actually have to be very large to be considered a reservoir. Any physical body whose thermal energy capacity is large relative to the amount of energy it supplies or absorbs can be modeled as one.

- The air in a room, for example, can be treated as a reservoir in the analysis of the heat dissipation from a TV set in the room, since the amount of heat transfer from the TV set to the room air is not large enough to have a noticeable effect on the room air temperature.

- **A reservoir that supplies energy in the form of heat is called a source, and one that absorbs energy in the form of heat is called a sink** (Fig. 6–7). Thermal energy reservoirs are often referred to as **heat reservoirs** since they supply or absorb energy in the form of heat.

- If it is not carefully controlled, thermal pollution can seriously disrupt marine life in lakes and rivers. However, by careful design and management, the waste energy dumped into large bodies of water can be used to improve the quality of marine life by keeping the local temperature increases within safe and desirable levels.

- Heat transfer from industrial sources to the environment is of major concern to environmentalists as well as to engineers. Irresponsible management of waste energy can significantly increase the temperature of portions of the environment, causing what is called *thermal pollution*.

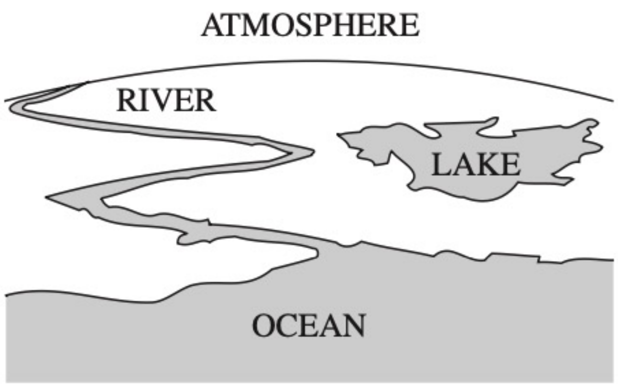


FIGURE 6–6

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

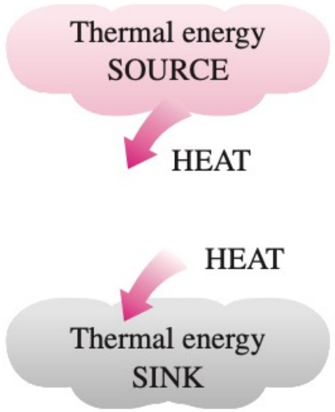


FIGURE 6–7

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

HEAT ENGINES

- **As pointed out earlier, work can easily be converted to other forms of energy, but converting other forms of energy to work is not that easy.**

- **The mechanical work done by the shaft shown in Fig. 6–8, for example, is first converted to the internal energy of the water.**

- **This energy may then leave the water as heat. We know from experience that any attempt to reverse this process will fail.**

- **That is, transferring heat to the water does not cause the shaft to rotate. *From this and other observations, we conclude that work can be converted to heat directly and completely, but converting heat to work requires the use of some special devices.***

- **These devices are called heat engines.**

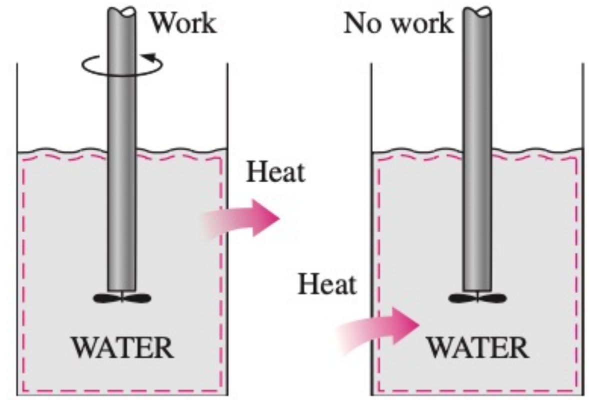


FIGURE 6–8
Work can always be converted to heat directly and completely, but the reverse is not true.

- Heat engines differ considerably from one another, but all can be characterized by the following (Fig. 6–9):

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.

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.**

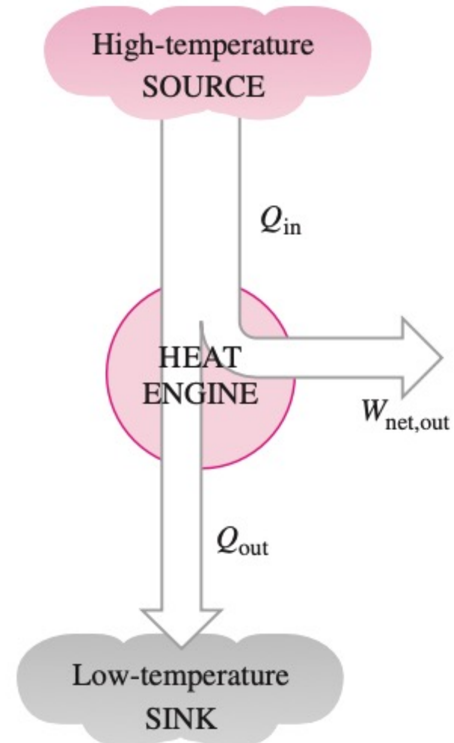


FIGURE 6–9
Part of the heat received by a heat engine is converted to work, while the rest is rejected to a sink.

- The term *heat engine* is often used in a broader sense to include work- producing devices that do not operate in a thermodynamic cycle. Engines that involve internal combustion such as gas turbines and car engines fall into this category.

- **These devices operate in a mechanical cycle but not in a thermodynamic cycle since the working fluid (the combustion gases) does not undergo a complete cycle.**

- Instead of being cooled to the initial temperature, the exhaust gases are purged and replaced by fresh air-and-fuel mixture at the end of the cycle.

- **The work-producing device that best fits into the definition of a heat engine is the *steam power plant*, which is an external-combustion engine**.

- That is, combustion takes place outside the engine, and the thermal energy released during this process is transferred to the steam as heat.

- The schematic of a basic steam power plant is shown in Fig. 6–10. This is a rather simplified diagram, and the discussion of actual steam power plants is given in later chapters. The various quantities shown on this figure are as follows:

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

Notice that the directions of the heat and work interactions are indicated by the subscripts *in* and *out*. Therefore, all four of the described quantities are always *positive*.

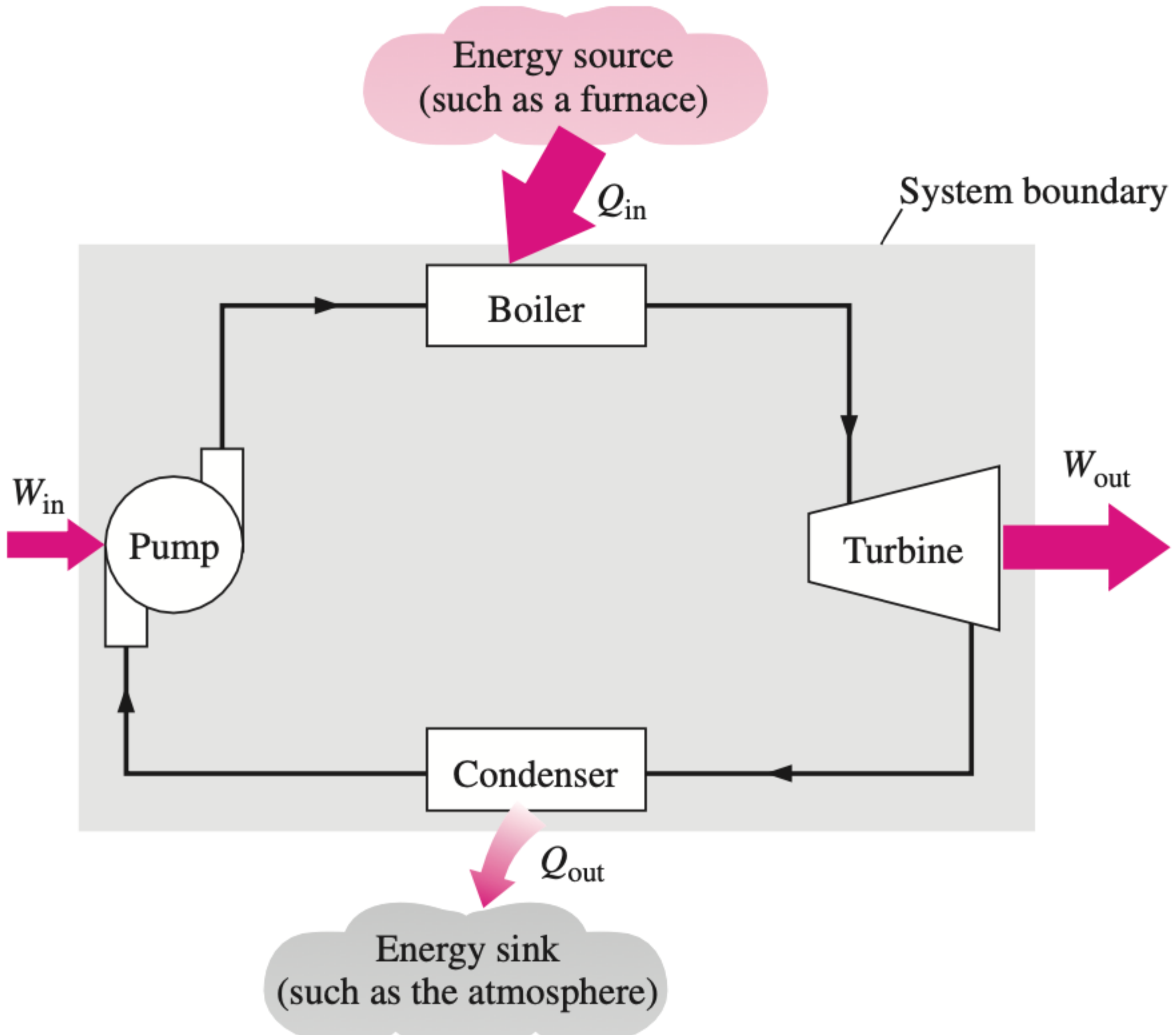


FIGURE 6–10

Schematic of a steam power plant.

The net work output of this power plant is simply the difference between the total work output of the plant and the total work input (Fig. 6–11):

$$W_{\text{net,out}} = W_{\text{out}} - W_{\text{in}} \qquad \text{(kJ)} \tag{6–1}$$

The net work can also be determined from the heat transfer data alone. The four components of the steam power plant involve mass flow in and out, and therefore they should be treated as open systems. These components, together with the connecting pipes, however, always contain the same fluid (not counting the steam that may leak out, of course). No mass enters or leaves this combination system, which is indicated by the shaded area on Fig. 6–10; thus, it can be analyzed as a closed system. Recall that for a closed system undergoing a cycle, the change in internal energy ΔU is zero, and therefore the net work output of the system is also equal to the net heat transfer to the system:

$$W_{\text{net,out}} = Q_{\text{in}} - Q_{\text{out}} \qquad \text{(kJ)} \tag{6–2}$$

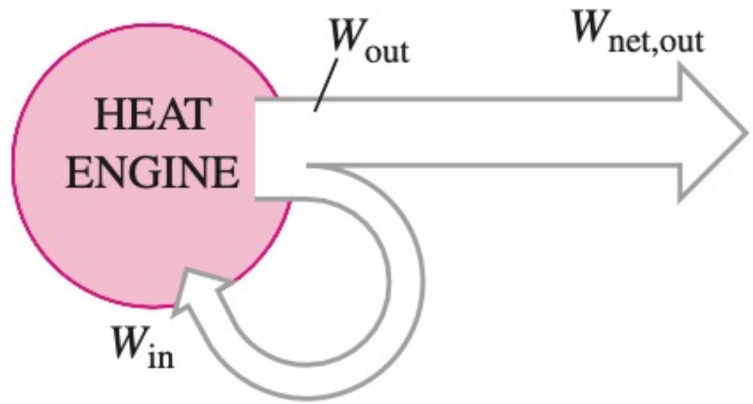


FIGURE 6–11

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

Thermal Efficiency

In Eq. 6–2, Q_{out} represents the magnitude of the energy wasted in order to complete the cycle. But Q_{out} is never zero; thus, the net work output of a heat engine is always less than the amount of heat input. That is, only part of the heat transferred to the heat engine is converted to work. The fraction of the heat input that is converted to net work output is a measure of the performance of a heat engine and is called the **thermal efficiency** η_{th} (Fig. 6–12).

For heat engines, the desired output is the net work output, and the required input is the amount of heat supplied to the working fluid. Then the thermal efficiency of a heat engine can be expressed as

$$\text{Thermal efficiency} = \frac{\text{Net work output}}{\text{Total heat input}} \tag{6–3}$$

or

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} \tag{6–4}$$

It can also be expressed as

$$\eta_{th} = 1 - \frac{Q_{out}}{Q_{in}} \tag{6–5}$$

since Wnet,out = Qin - Qout.

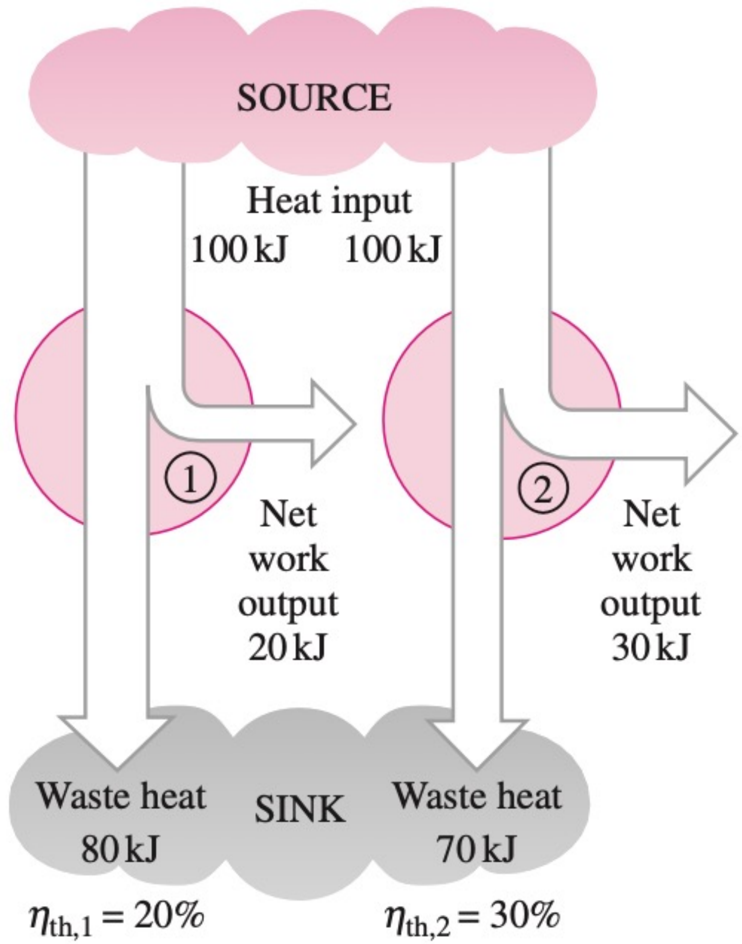


FIGURE 6–12

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

Cyclic devices of practical interest such as heat engines, refrigerators, and heat pumps operate between a high-temperature medium (or reservoir) at temperature T_H and a low-temperature medium (or reservoir) at temperature T_L. To bring uniformity to the treatment of heat engines, refrigerators, and heat pumps, we define these two quantities:

Q_H = magnitude of heat transfer between the cyclic device and the high-temperature medium at temperature T_H

Q_L = magnitude of heat transfer between the cyclic device and the low-temperature medium at temperature T_L

Notice that both Q_L and Q_H are defined as *magnitudes* and therefore are positive quantities. The direction of Q_H and Q_L is easily determined by inspection. Then the net work output and thermal efficiency relations for any heat engine (shown in Fig. 6–13) can also be expressed as

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

and

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

or

$$\eta_{\text{th}} = 1 - \frac{Q_L}{Q_H} \qquad \textbf{(6–6)}$$

- The thermal efficiency of a heat engine is always less than unity since both *QL* and *QH* are defined as positive quantities

- Thermal efficiency is a measure of how efficiently a heat engine converts the heat that it receives to work. Heat engines are built for the purpose of converting heat to work, and engineers are constantly trying to improve the efficiencies of these devices since increased efficiency means less fuel consumption and thus lower fuel bills and less pollution.

- The thermal efficiencies of work-producing devices are relatively low. Ordinary spark-ignition automobile engines have a thermal efficiency of about 25 percent. That is, an automobile engine converts about 25 percent of the chemical energy of the gasoline to mechanical work.

- This number is as high as 40 percent for diesel engines and large gas-turbine plants and as high as 60 percent for large combined gas-steam power plants. Thus, even with the most efficient heat engines available today, almost one-half of the energy supplied ends up in the rivers, lakes, or the atmosphere as waste or useless energy (Fig. 6–14).

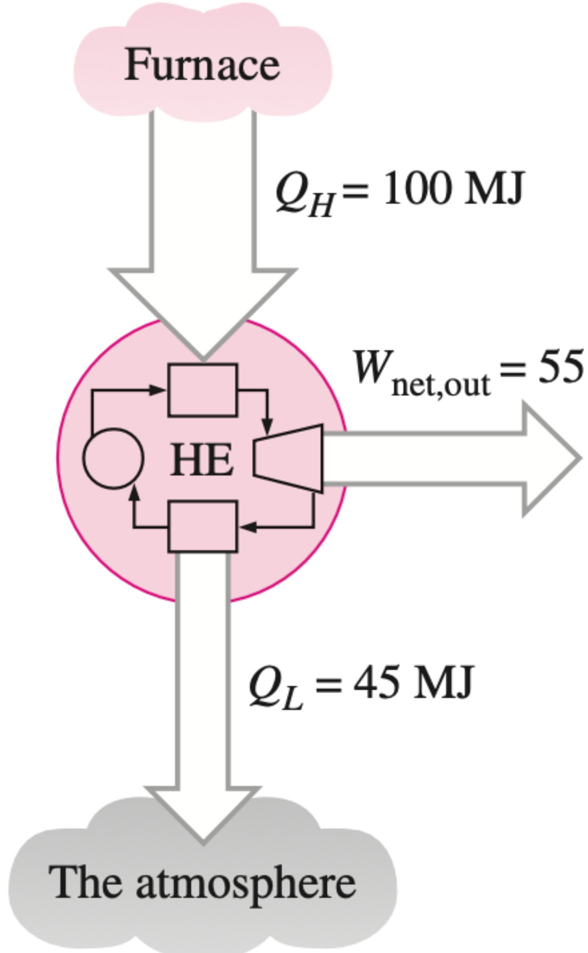


FIGURE 6–14

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

Can We Save Q_{out}?

- **In a steam power plant, the condenser is the device where large quantities of waste heat is rejected to rivers, lakes, or the atmosphere.** Then one may ask, can we not just take the condenser out of the plant and save all that waste energy?

- The answer to this question is, unfortunately, a firm *no* for the simple reason that **without a heat rejection process in a condenser, the cycle cannot be completed**. (**Cyclic devices such as steam power plants cannot run continuously unless the cycle is completed**.)

- This is demonstrated next with the help of a simple heat engine. Consider the simple heat engine shown in Fig. 6–15 that is used to lift weights. It consists of a piston–cylinder device with two sets of stops.

- The working fluid is the gas contained within the cylinder. Initially, the gas temperature is 30°C. The piston, which is loaded with the weights, is resting on top of the lower stops.

- Now 100 kJ of heat is transferred to the gas in the cylinder from a source at 100°C, causing it to expand and to raise the loaded piston until the piston reaches the upper stops, as shown in the figure. At this point, the load is removed, and the gas temperature is observed to be 90°C.

- **The work done on the load during this expansion process is equal to the increase in its potential energy, say 15 kJ. Even under ideal conditions (weightless piston, no friction, no heat losses, and quasi-equilibrium expansion), the amount of heat supplied to the gas is greater than the work done since part of the heat supplied is used to raise the temperature of the gas.**

- Now let us try to answer this question: *Is it possible to transfer the 85 kJ of excess heat at 90°C back to the reservoir at 100°C for later use?* If it is, then we will have a heat engine that can have a thermal efficiency of 100 percent under ideal conditions.

- **The answer to this question is again *no*, for the very simple reason that heat is always transferred from a high- temperature medium to a low-temperature one, and never the other way around.**

- Therefore, we cannot cool this gas from 90 to 30°C by transferring heat to a reservoir at 100°C. Instead, we have to bring the system into contact with a low-temperature reservoir, say at 20°C, so that the gas can return to its initial state by rejecting its 85 kJ of excess energy as heat to this reservoir.

- **This energy cannot be recycled, and it is properly called *waste energy*.**

- We conclude from this discussion that 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.

- The requirement that a heat engine exchange heat with at least two reservoirs for continuous operation forms the basis for the Kelvin–Planck expression of the second law of thermodynamics discussed later in this section.

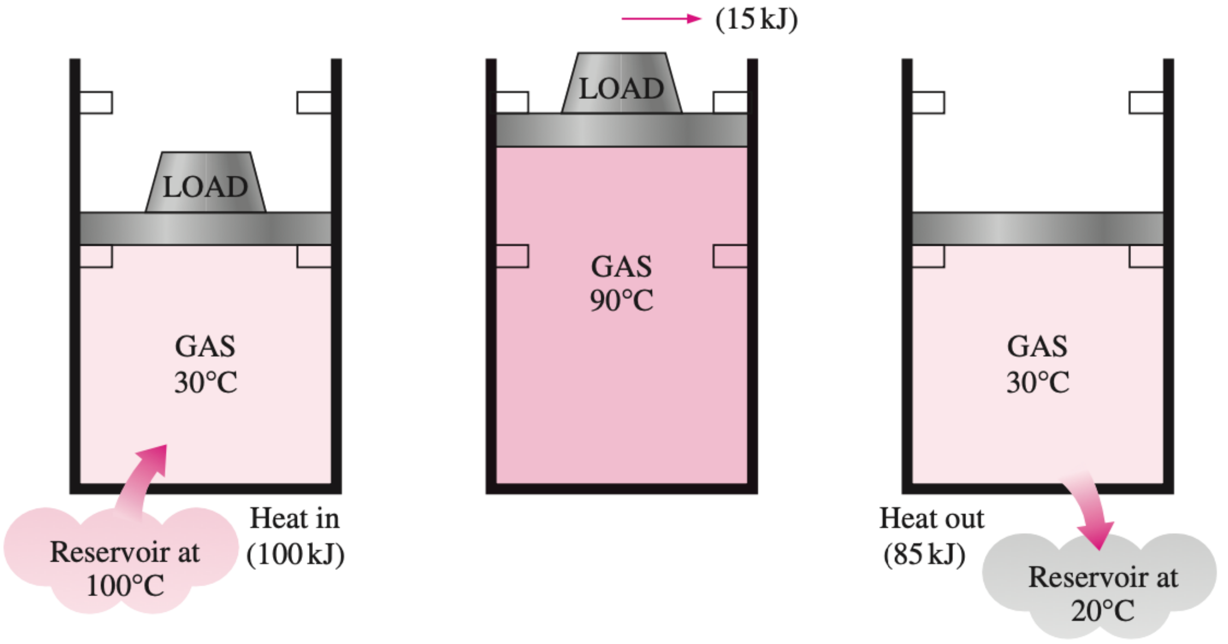


FIGURE 6–15

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

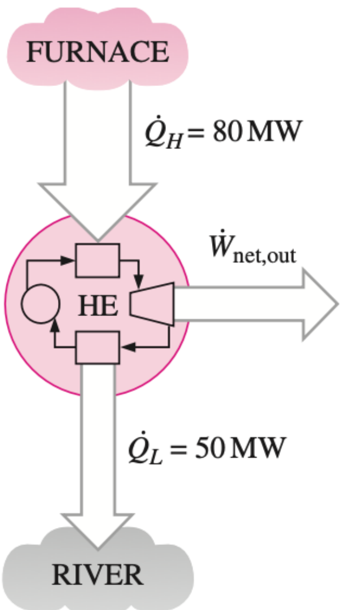


FIGURE 6–16

Schematic for Example 6–1.

EXAMPLE 6–1 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 The rates of heat transfer to and from a heat engine are given. The net power output and the thermal efficiency are to be determined.

Assumptions Heat losses through the pipes and other components are negligible.

Analysis A schematic of the heat engine is given in Fig. 6–16. The furnace serves as the high-temperature reservoir for this heat engine and the river as the low-temperature reservoir. The given quantities can be expressed as

$$\dot{Q}_H = 80 \text{ MW} \quad \text{and} \quad \dot{Q}_L = 50 \text{ MW}$$

The net power output of this heat engine is

$$\dot{W}_{\text{net,out}} = \dot{Q}_H - \dot{Q}_L = (80 - 50) \text{ MW} = \mathbf{30 \text{ MW}}$$

Then the thermal efficiency is easily determined to be

$$\eta_{\text{th}} = \frac{\dot{W}_{\text{net,out}}}{\dot{Q}_H} = \frac{30 \text{ MW}}{80 \text{ MW}} = \mathbf{0.375} \text{ (or } 37.5\%\text{)}$$

Discussion Note that the heat engine converts 37.5 percent of the heat it receives to work.

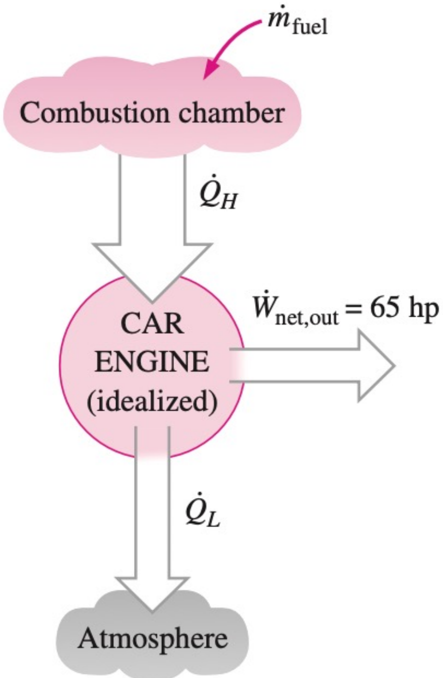


FIGURE 6–17
Schematic for Example 6–2.

EXAMPLE 6–2 Fuel Consumption Rate of a Car

A car engine with a power output of 65 hp has a thermal efficiency of 24 percent. Determine the fuel consumption rate of this car if the fuel has a heating value of 19,000 Btu/lbm (that is, 19,000 Btu of energy is released for each lbm of fuel burned).

Solution The power output and the efficiency of a car engine are given. The rate of fuel consumption of the car is to be determined.
Assumptions The power output of the car is constant.
Analysis A schematic of the car engine is given in Fig. 6–17. The car engine is powered by converting 24 percent of the chemical energy released during the combustion process to work. The amount of energy input required to produce a power output of 65 hp is determined from the definition of thermal efficiency to be

$$\dot{Q}_H = \frac{\dot{W}_{net,out}}{\eta_{th}} = \frac{65\text{ hp}}{0.24}\left(\frac{2545\text{ Btu/h}}{1\text{ hp}}\right) = 689{,}270\text{ Btu/h}$$

To supply energy at this rate, the engine must burn fuel at a rate of

$$\dot{m} = \frac{689{,}270\text{ Btu/h}}{19{,}000\text{ Btu/lbm}} = \mathbf{36.3\text{ lbm/h}}$$

since 19,000 Btu of thermal energy is released for each lbm of fuel burned.
Discussion Note that if the thermal efficiency of the car could be doubled, the rate of fuel consumption would be reduced by half.

The Second Law of Thermodynamics: Kelvin–Planck Statement

- We have demonstrated earlier with reference to the heat engine shown in Fig. 6–15 that, even under ideal conditions, a heat engine must reject some heat to a low-temperature reservoir in order to complete the cycle.

- That is, no heat engine can convert all the heat it receives to useful work. This limitation on the thermal efficiency of heat engines forms the basis for the Kelvin–Planck statement of the second law of thermodynamics, which is expressed as follows:

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.

- That is, a heat engine must exchange heat with a low-temperature sink as well as a high-temperature source to keep operating.

- **The Kelvin–Planck statement can also be expressed as *no heat engine can have a thermal efficiency of 100 percent* (Fig. 6–18), or as *for a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace*.**

- Note that the impossibility of having a 100 percent 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.

- Later in this chapter, we develop a relation for the maximum thermal efficiency of a heat engine. We also demonstrate that this maximum value depends on the reservoir temperatures only.

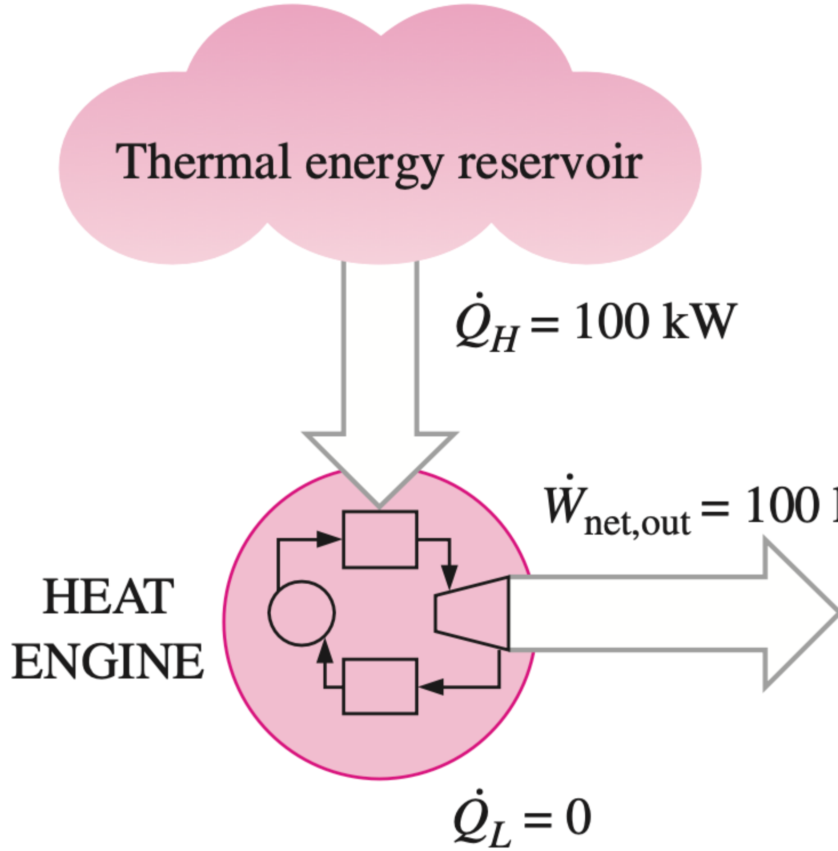


FIGURE 6–18

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

REFRIGERATORS AND HEAT PUMPS

- We all know from experience that heat is transferred in the direction of decreasing temperature, that is, from high-temperature mediums 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 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*, which involves four main components: a compressor, a condenser, an expansion valve, and an evaporator, as shown in Fig. 6–19.

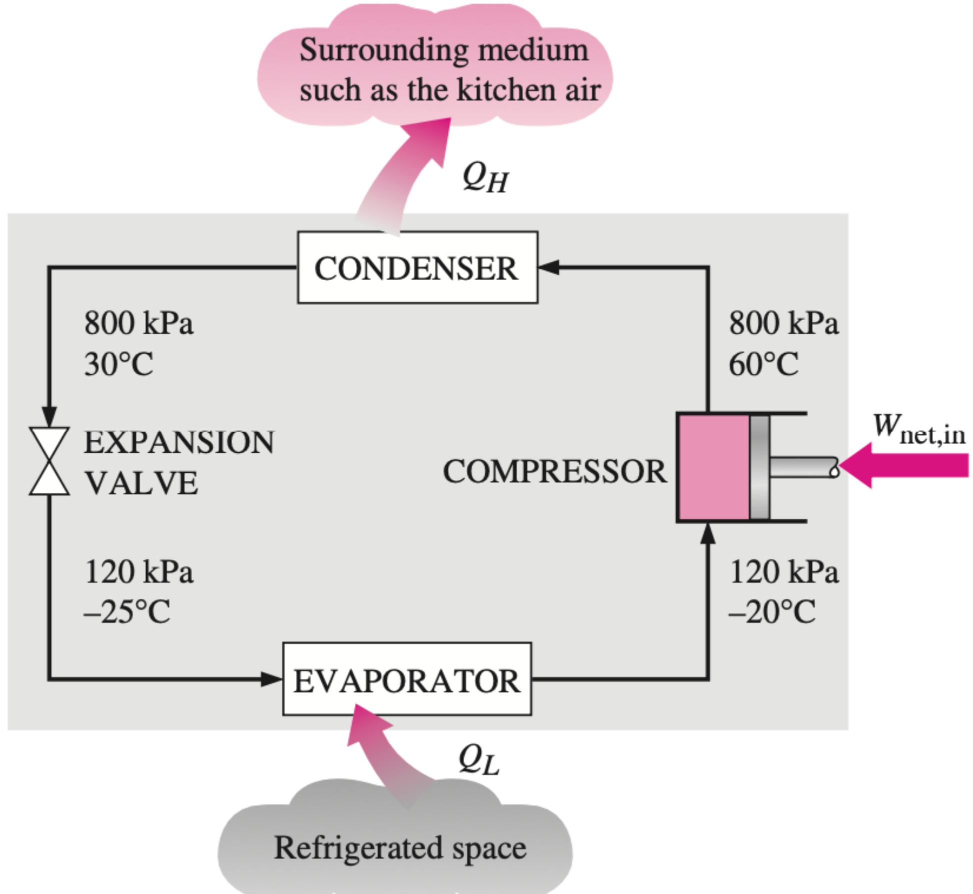


FIGURE 6–19

Basic components of a refrigeration system and typical operating conditions.

- The refrigerant enters the compressor as a vapor and is compressed to the condenser pressure. It leaves the compressor at a relatively high temperature and cools down and condenses as it flows through the coils of the condenser by rejecting heat to the surrounding medium.

- It then enters a capillary tube where its pressure and temperature drop drastically due to the throttling effect. The low-temperature refrigerant then enters the evaporator, where it evaporates by absorbing heat from the refrigerated space.

- The cycle is completed as the refrigerant leaves the evaporator and reenters the compressor.

- 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.

- A refrigerator is shown schematically in Fig. 6–20. 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 environment at temperature T_H, and $W_{net,in}$ is the net work input to the refrigerator. As discussed before, Q_L and Q_H represent magnitudes and thus are positive quantities.

Coefficient of Performance

The *efficiency* of a refrigerator is expressed in terms of the **coefficient of performance** (COP), denoted by COP_R. The objective of a refrigerator is to remove heat (Q_L) from the refrigerated space. To accomplish this objective, it requires a work input of $W_{\text{net,in}}$. Then the COP of a refrigerator can be expressed as

$$\text{COP}_\text{R} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_L}{W_{\text{net,in}}} \qquad \textbf{(6–7)}$$

This relation can also be expressed in rate form by replacing Q_L by $\dot{Q}_L$ and $W_{\text{net,in}}$ by $\dot{W}_{\text{net,in}}$.

The conservation of energy principle for a cyclic device requires that

$$W_{\text{net,in}} = Q_H - Q_L \qquad (\text{kJ}) \qquad \textbf{(6–8)}$$

$$\mathrm{COP_R} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1} \qquad \textbf{(6–9)}$$

Notice that the value of $\mathrm{COP_R}$ can be *greater than unity*. That is, the amount of heat removed from the refrigerated space can be greater than the amount of work input. This is in contrast to the thermal efficiency, which can never be greater than 1. In fact, one reason for expressing the efficiency of a refrigerator by another term—the coefficient of performance—is the desire to avoid the oddity of having efficiencies greater than unity.

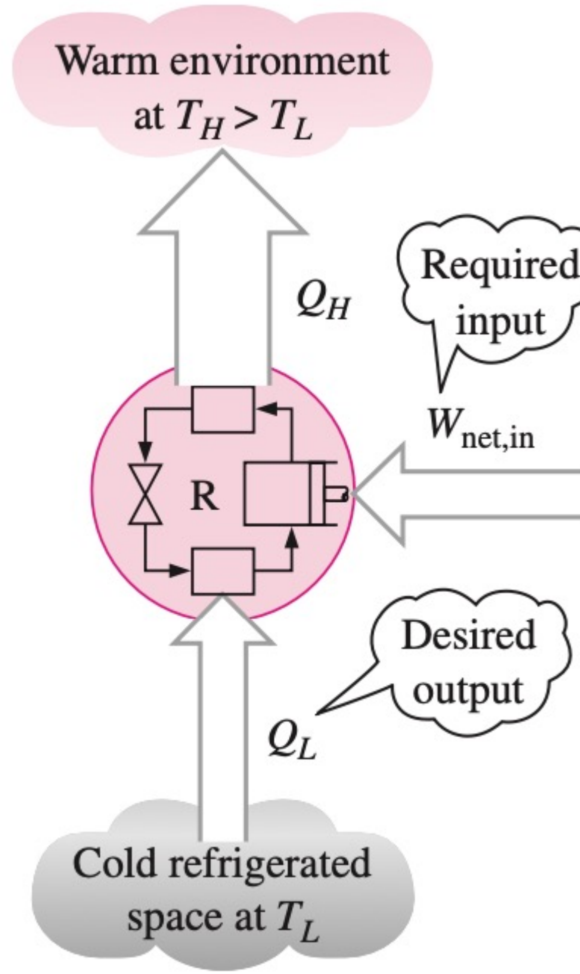


FIGURE 6–20

The objective of a refrigerator is to remove Q_L from the cooled space.

- Heat Pumps

- **Another device that transfers heat from a low-temperature medium to a high-temperature one is the heat pump, shown schematically in Fig. 6–21.**

- Refrigerators and heat pumps operate on the same cycle but differ in their objectives. 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 the high-temperature medium such as a house (Fig. 6–22).
- An ordinary refrigerator that is placed in the window of a house with its door open to the cold outside air in winter will function as a heat pump since it will try to cool the outside by absorbing heat from it and rejecting this heat into the house through the coils behind it (Fig. 6–23).

- The measure of performance of a heat pump is also expressed in terms of the **coefficient of performance** COPHP, defined as

$$\mathrm{COP_{HP}} = \frac{\text{Desired output}}{\text{Required input}} = \frac{Q_H}{W_{\mathrm{net,in}}} \tag{6–10}$$

which can also be expressed as

$$\mathrm{COP_{HP}} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H} \tag{6–11}$$

A comparison of Eqs. 6–7 and 6–10 reveals that

$$\mathrm{COP_{HP}} = \mathrm{COP_R} + 1 \tag{6–12}$$

for fixed values of Q_L and Q_H. This relation implies that the coefficient of performance of a heat pump is always greater than unity since $\mathrm{COP_R}$ is a positive quantity. That is, a heat pump will function, at worst, as a resistance heater, supplying as much energy to the house as it consumes. In reality, however, part of Q_H is lost to the outside air through piping and other devices, and $\mathrm{COP_{HP}}$ may drop below unity when the outside air temperature is too low. When this happens, the system usually switches to a resistance heating mode. Most heat pumps in operation today have a seasonally averaged COP of 2 to 3.

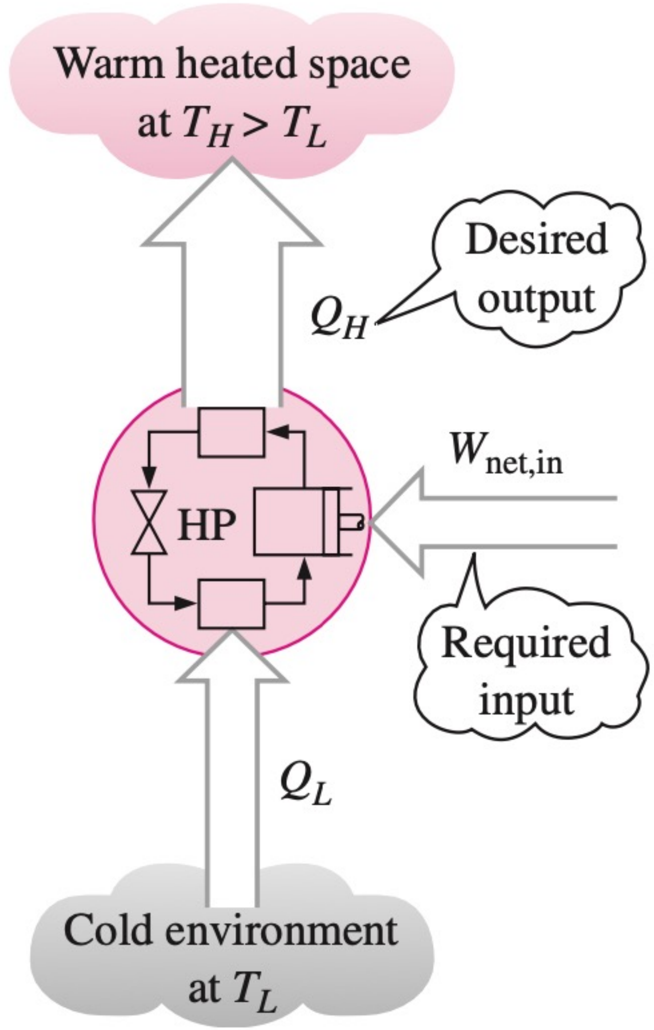


FIGURE 6–21

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

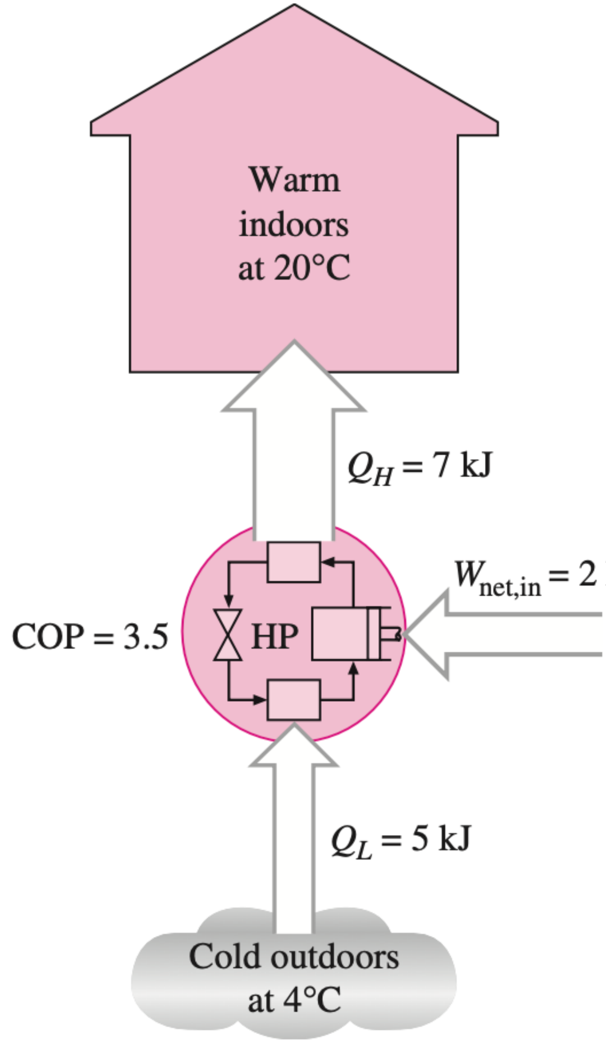


FIGURE 6–22

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

- Most existing heat pumps use the cold outside air as the heat source in winter, and they are referred to as *air-source heat pumps*.

- The COP of such heat pumps is about 3.0 at design conditions. Air-source heat pumps are not appropriate for cold climates since their efficiency drops consider- ably when temperatures are below the freezing point.

- In such cases, geo- thermal (also called ground-source) heat pumps that use the ground as the heat source can be used. Geothermal heat pumps require the burial of pipes in the ground 1 to 2 m deep. Such heat pumps are more expensive to install, but they are also more efficient (up to 45 percent more efficient than air-source heat pumps). The COP of ground-source heat pumps is about 4.0.

- **Air conditioners are basically refrigerators whose refrigerated space is a room or a building instead of the food compartment. A window air- conditioning unit cools a room by absorbing heat from the room air and discharging it to the outside.**

- The same air-conditioning unit can be used as a heat pump in winter by installing it backwards as shown in Fig. 6–23. In this mode, the unit absorbs heat from the cold outside and delivers it to the room.

- Air-conditioning systems that are equipped with proper controls and a reversing valve operate as air conditioners in summer and as heat pumps in winter.

- **The performance of refrigerators and air conditioners in the United States is often expressed in terms of *the energy efficiency rating (EER), which is the amount of heat removed from the cooled space in Btu's for 1 Wh (watt- hour) of electricity consumed.***

- Considering that 1 kWh = 3412 Btu and thus 1 Wh = 3.412 Btu, a unit that removes 1 kWh of heat from the cooled space for each kWh of electricity it consumes (COP = 1) will have an EER of 3.412. Therefore, the relation between EER and COP is
- EER = 3.412 COPR

- Most air conditioners have an EER between 8 and 12 (a COP of 2.3 to 3.5). A high-efficiency heat pump manufactured by the Trane Company using a reciprocating variable-speed compressor is reported to have a COP of 3.3 in the heating mode and an EER of 16.9 (tCOP of 5.0) in he air- conditioning mode.

- Variable-speed compressors and fans allow the unit to operate at maximum efficiency for varying heating/cooling needs and weather conditions as determined by a microprocessor.

- In the air-conditioning mode, for example, they operate at higher speeds on hot days and at lower speeds on cooler days, enhancing both efficiency and comfort

- The EER or COP of a refrigerator decreases with decreasing refrigera- tion temperature. Therefore, it is not economical to refrigerate to a lower temperature than needed.

- The COPs of refrigerators are in the range of 2.6–3.0 for cutting and preparation rooms; 2.3–2.6 for meat, deli, dairy, and produce; 1.2–1.5 for frozen foods; and 1.0–1.2 for ice cream units.

- Note that the COP of freezers is about half of the COP of meat refrigera- tors, and thus it costs twice as much to cool the meat products with refrigerated air that is cold enough to cool frozen foods.

- It is good energy conservation practice to use separate refrigeration systems to meet different refrigeration needs.

EXAMPLE 6–3 Heat Rejection by a Refrigerator

The food compartment of a refrigerator, shown in Fig. 6–24, is maintained at 4°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 (*a*) the coefficient of performance of the refrigerator and (*b*) the rate of heat rejection to the room that houses the refrigerator.

Solution The power consumption of a refrigerator is given. The COP and the rate of heat rejection are to be determined.

Assumptions Steady operating conditions exist.

Analysis (*a*) The coefficient of performance of the refrigerator is

$$\text{COP}_R = \frac{\dot{Q}_L}{\dot{W}_{\text{net,in}}} = \frac{360 \text{ kJ/min}}{2 \text{ kW}}\left(\frac{1 \text{ kW}}{60 \text{ kJ/min}}\right) = \mathbf{3}$$

That is, 3 kJ of heat is removed from the refrigerated space for each kJ of work supplied.

(*b*) The rate at which heat is rejected to the room that houses the refrigerator is determined from the conservation of energy relation for cyclic devices,

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{\text{net,in}} = 360 \text{ kJ/min} + (2 \text{ kW})\left(\frac{60 \text{ kJ/min}}{1 \text{ kW}}\right) = \mathbf{480 \text{ kJ/min}}$$

Discussion Notice that both the energy removed from the refrigerated space as heat and the energy supplied to the refrigerator as electrical work eventually show up in the room air and become part of the internal energy of the air. This demonstrates that energy can change from one form to another, can move from one place to another, but is never destroyed during a process.

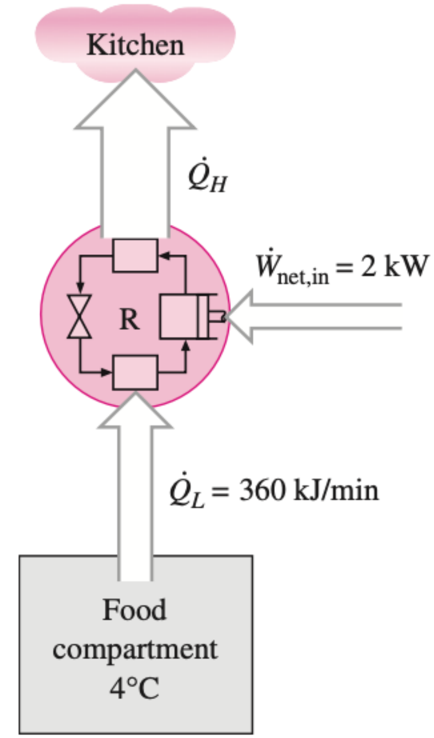


FIGURE 6–24

Schematic for Example 6–3.

EXAMPLE 6–4 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°C. On a day when the outdoor air temperature drops to −2°C, the house is estimated to lose heat at a rate of 80,000 kJ/h. If the heat pump under these conditions has a COP of 2.5, determine (*a*) the power consumed by the heat pump and (*b*) the rate at which heat is absorbed from the cold outdoor air.

Solution The COP of a heat pump is given. The power consumption and the rate of heat absorption are to be determined.

Assumptions Steady operating conditions exist.

Analysis (*a*) The power consumed by this heat pump, shown in Fig. 6–25, is determined from the definition of the coefficient of performance to be

$$\dot{W}_{\text{net,in}} = \frac{\dot{Q}_H}{\text{COP}_{\text{HP}}} = \frac{80{,}000\ \text{kJ/h}}{2.5} = \mathbf{32{,}000\ kJ/h}\ (\text{or } 8.9\ \text{kW})$$

(*b*) The house is losing heat at a rate of 80,000 kJ/h. If the house is to be maintained at a constant temperature of 20°C, the heat pump must deliver

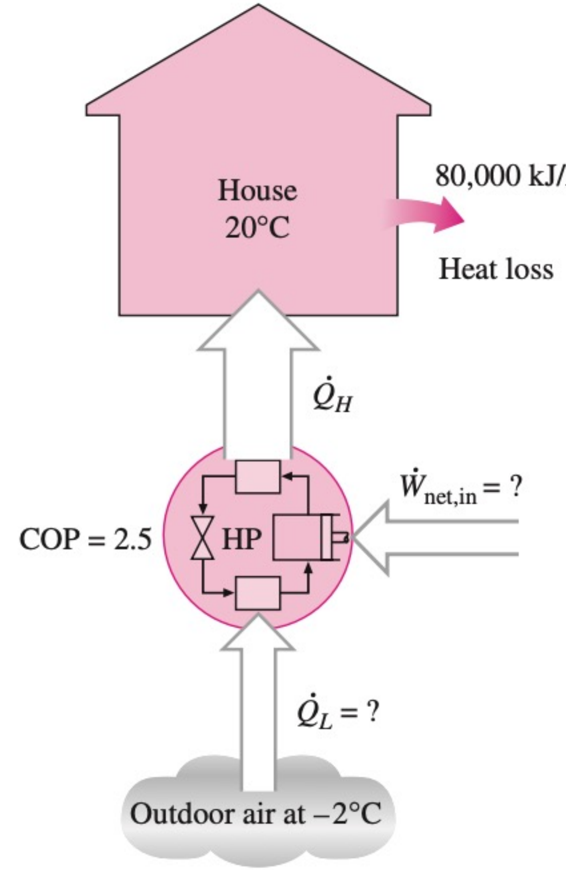


FIGURE 6–25
Schematic for Example 6–4.

heat to the house at the same rate, that is, at a rate of 80,000 kJ/h. Then the rate of heat transfer from the outdoor becomes

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{\text{net,in}} = (80{,}000 - 32{,}000)\ \text{kJ/h} = \mathbf{48{,}000\ kJ/h}$$

Discussion Note that 48,000 of the 80,000 kJ/h heat delivered to the house is actually extracted from the cold outdoor air. Therefore, we are paying only for the 32,000-kJ/h energy that is supplied as electrical work to the heat pump. If we were to use an electric resistance heater instead, we would have to supply the entire 80,000 kJ/h to the resistance heater as electric energy. This would mean a heating bill that is 2.5 times higher. This explains the popularity of heat pumps as heating systems and why they are preferred to simple electric resistance heaters despite their considerably higher initial cost.

The Second Law of Thermodynamics: Clausius Statement

- There are two classical statements of the second law—the Kelvin–Planck statement, which is related to heat engines and discussed in the preceding section, and the Clausius statement, which is related to refrigerators or heat pumps.

- The Clausius statement is expressed as follows:

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 is common knowledge that heat does not, of its own volition, transfer from a cold medium to a warmer one. The Clausius statement does not imply that a cyclic device that transfers heat from a cold medium to a warmer one is impossible to construct. In fact, this is precisely what a common household refrigerator does.

- **It simply states that a refrigerator cannot operate unless its compressor is driven by an external power source, such as an electric motor (Fig. 6–26).**

- 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.

- That is, it leaves a trace in the surroundings. Therefore, a household refrigerator is in complete compliance with the Clausius statement of the second law.

- Both the Kelvin–Planck and the Clausius statements of the second law are negative statements, and a negative statement cannot be proved.

- Like any other physical law, the second law of thermodynamics is based on experimental observations.

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

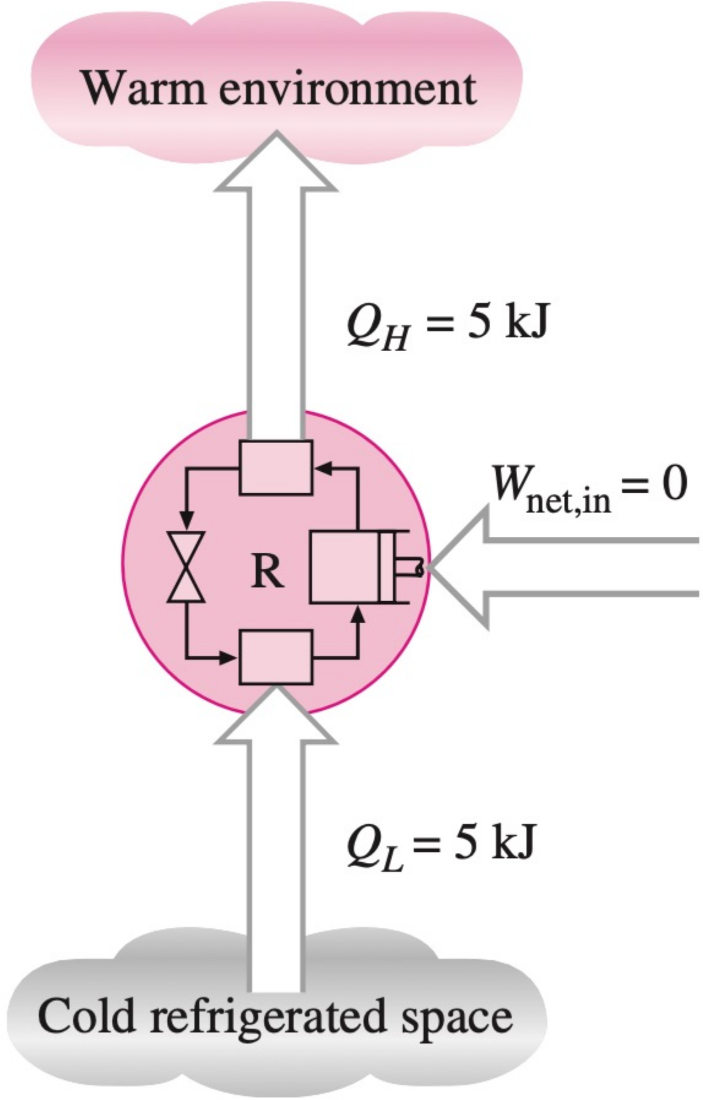
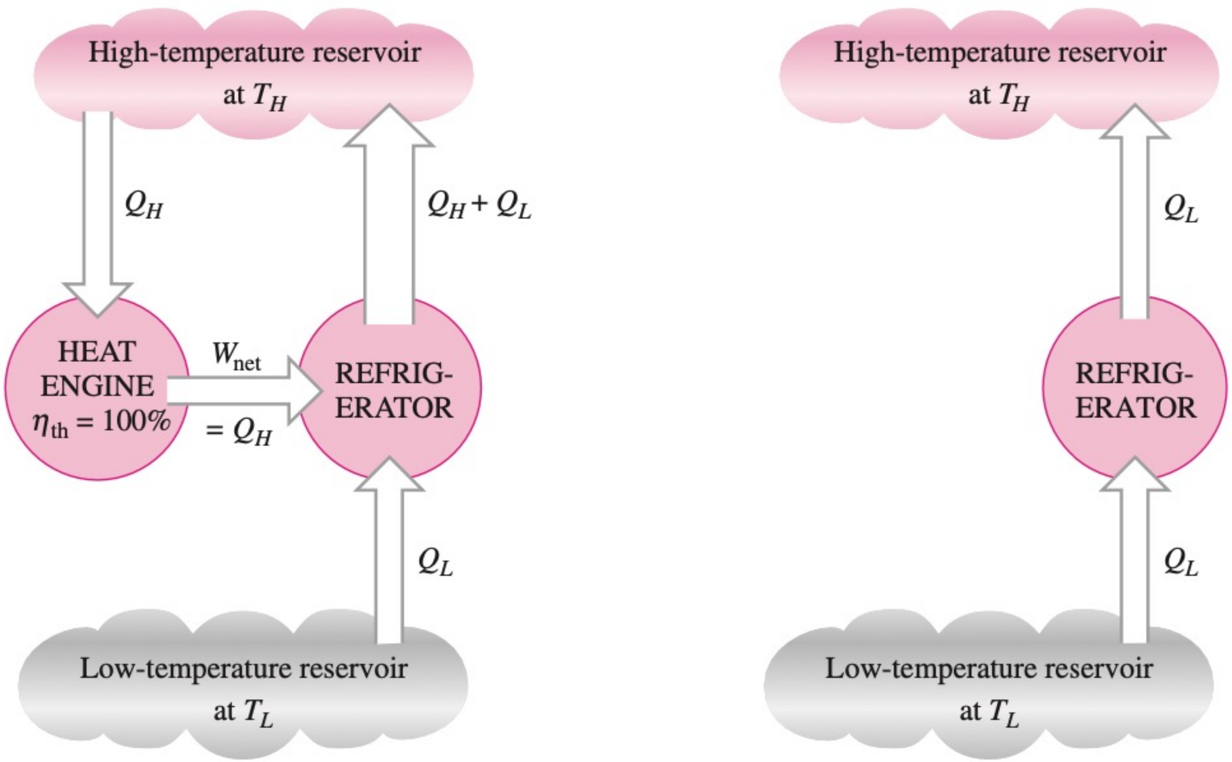


FIGURE 6–26

A refrigerator that violates the Clausius statement of the second law.

Equivalence of the Two Statements

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. This can be demonstrated as follows.**



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

(*b*) The equivalent refrigerator

FIGURE 6–27

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

REVERSIBLE AND IRREVERSIBLE PROCESSES

- The second law of thermodynamics states that no heat engine can have an efficiency of 100 percent. Then one may ask, What is the highest efficiency that a heat engine can possibly have? Before we can answer this question, we need to define an idealized process first, which is called the *reversible process*.

- The processes that were discussed at the beginning of this chapter occurred in a certain direction. Once having taken place, these processes cannot reverse themselves spontaneously and restore the system to its initial state. For this reason, they are classified as *irreversible processes*.

- Once a cup of hot coffee cools, it will not heat up by retrieving the heat it lost from the surroundings. If it could, the surroundings, as well as the system (coffee), would be restored to their original condition, and this would be a reversible process.

- **A reversible process is defined as a *process that can be reversed without leaving any trace on the surroundings* (Fig. 6–30). That is, both the system *and* the surroundings are returned to their initial states at the end of the reverse process. This is possible only if the net heat *and* net work exchange between the system and the surroundings is zero for the combined (original and reverse) process. Processes that are not reversible are called irreversible processes.**

- It should be pointed out that a system can be restored to its initial state following a process, regardless of whether the process is reversible or irreversible. But for reversible processes, this restoration is made without leaving any net change on the surroundings, whereas for irreversible processes, the surroundings usually do some work on the system and therefore does not return to their original state.

- Reversible processes actually do not occur in nature. They are merely *idealizations* of actual processes. Reversible processes can be approximated by actual devices, but they can never be achieved. That is, all the processes occurring in nature are irreversible.

- You may be wondering, then, *why* we are bothering with such fictitious processes. There are two reasons. First, they are easy to analyze, since a system passes through a series of equilibrium states during a reversible process; second, they serve as idealized models to which actual processes can be compared.

- In daily life, the concepts of Mr. Right and Ms. Right are also idealizations, just like the concept of a reversible (perfect) process. People who insist on finding Mr. or Ms. Right to settle down are bound to remain Mr. or Ms. Single for the rest of their lives.

- The possibility of finding the perfect prospective mate is no higher than the possibility of finding a perfect (reversible) process. Likewise, a person who insists on perfection in friends is bound to have no friends.

- **Engineers are interested in reversible processes because work-producing devices such as car engines and gas or steam turbines *deliver the most work*, and work-consuming devices such as compressors, fans, and pumps *consume the least work* when reversible processes are used instead of irreversible ones** (Fig. 6–31).

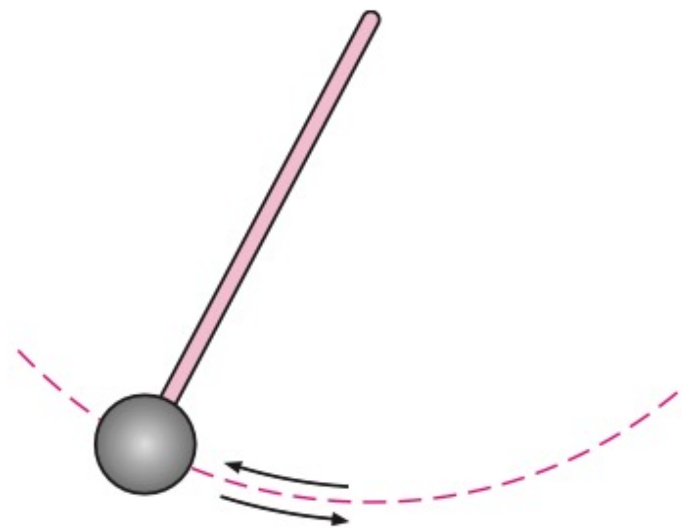
- Reversible processes can be viewed as *theoretical limits* for the corresponding irreversible ones. Some processes are more irreversible than others. We may never be able to have a reversible process, but we can certainly approach it.

- **The more closely we approximate a reversible process, the more work delivered by a work-producing device or the less work required by a work-consuming device.**

- The concept of reversible processes leads to the definition of the second- law efficiency for actual processes, which is the degree of approximation to the corresponding reversible processes.

- This enables us to compare the performance of different devices that are designed to do the same task on the basis of their efficiencies. The better the design, the lower the irreversibilities and the higher the second-law efficiency.

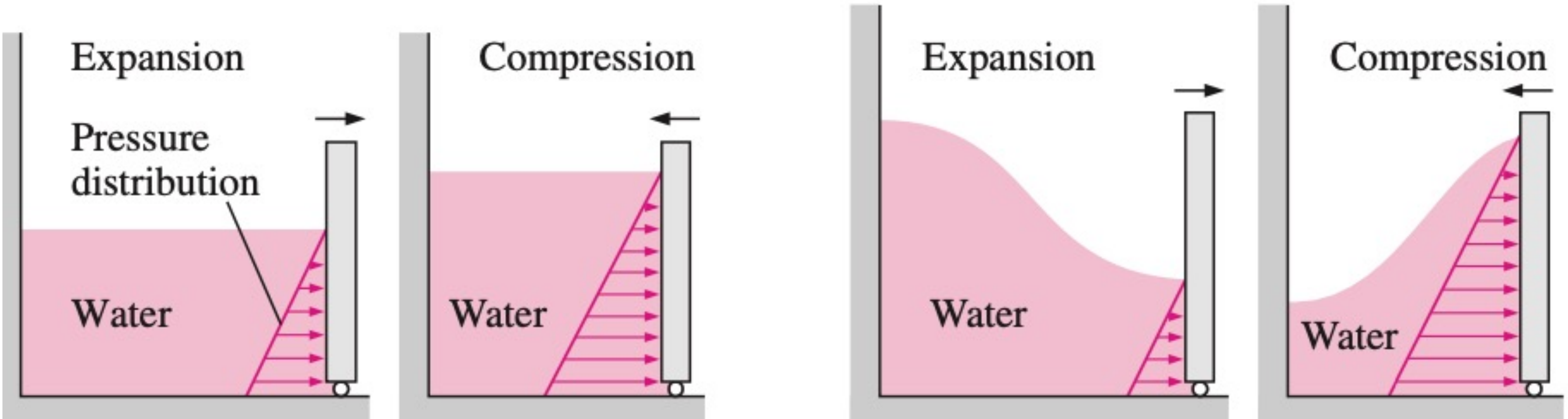
(*b*) Quasi-equilibrium expansion and compression of a gas



(*a*) Frictionless pendulum

FIGURE 6–30

Two familiar reversible processes.



(*a*) Slow (reversible) process (*b*) Fast (irreversible) process

FIGURE 6–31

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. A reversible process involves none of these. Some of the frequently encountered irreversibilities are discussed briefly below.

- **Friction is a familiar form of irreversibility associated with bodies in motion**. When two bodies in contact are forced to move relative to each other (a piston in a cylinder, for example, as shown in Fig. 6–32), a friction force that opposes the motion develops at the interface of these two bodies, and some work is needed to overcome this friction force.

- The energy sup- plied as work is eventually converted to heat during the process and is transferred to the bodies in contact, as evidenced by a temperature rise at the interface.

Irreversibilities

- When the direction of the motion is reversed, the bodies are restored to their original position, but the interface does not cool, and heat is not converted back to work. Instead, more of the work is converted to heat while overcoming the friction forces that also oppose the reverse motion.

- Since the system (the moving bodies) and the surroundings cannot be returned to their original states, this process is irreversible. Therefore, any process that involves friction is irreversible. The larger the friction forces involved, the more irreversible the process is.

- Friction does not always involve two solid bodies in contact. It is also encountered between a fluid and solid and even between the layers of a fluid moving at different velocities.

- A considerable fraction of the power produced by a car engine is used to overcome the friction (the drag force) between the air and the external surfaces of the car, and it eventually becomes part of the internal energy of the air. It is not possible to reverse this process and recover that lost power, even though doing so would not violate the conservation of energy principle.

- Another example of irreversibility is the **unrestrained expansion of a gas** separated from a vacuum by a membrane, as shown in Fig. 6–33. When the membrane is ruptured, the gas fills the entire tank.

- The only way to restore the system to its original state is to compress it to its initial volume, while transferring heat from the gas until it reaches its initial temperature.

- From the conservation of energy considerations, it can easily be shown that the amount of heat transferred from the gas equals the amount of work done on the gas by the surroundings. The restoration of the surroundings involves conversion of this heat completely to work, which would violate the second law. Therefore, unrestrained expansion of a gas is an irreversible process.

- A third form of irreversibility familiar to us all is **heat transfer** through a finite temperature difference. Consider a can of cold soda left in a warm room (Fig. 6–34).

- Heat is transferred from the warmer room air to the cooler soda. The only way this process can be reversed and the soda restored to its original temperature is to provide refrigeration, which requires some work input.

- At the end of the reverse process, the soda will be restored to its initial state, but the surroundings will not be. The internal energy of the surroundings will increase by an amount equal in magnitude to the work supplied to the refrigerator.

- The restoration of the surroundings to the initial state can be done only by converting this excess internal energy completely to work, which is impossible to do without violating the second law.

- Since only the system, not both the system and the surroundings, can be restored to its initial condition, heat transfer through a finite temperature difference is an irreversible process.

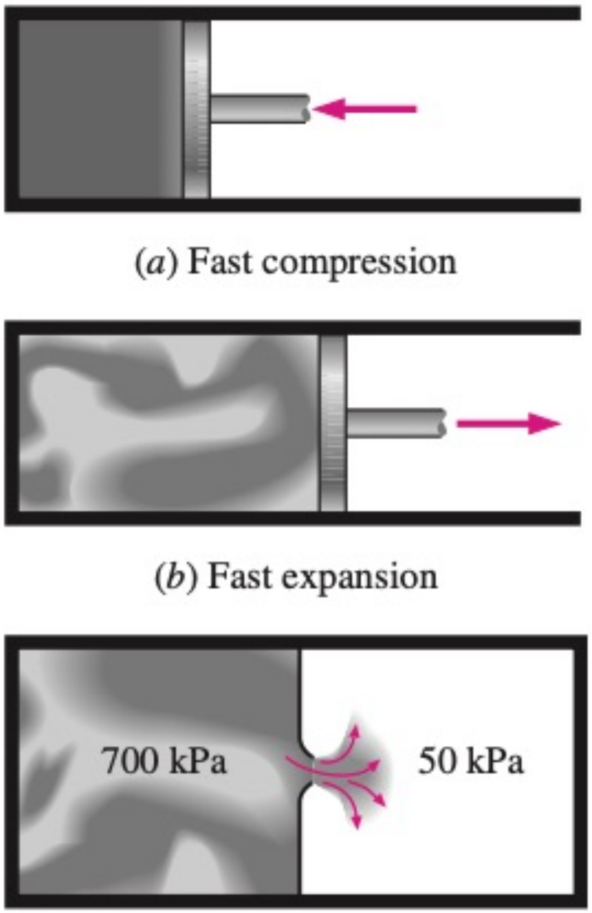
- Heat transfer can occur only when there is a temperature difference between a system and its surroundings. Therefore, it is physically impossible to have a reversible heat transfer process.

- But a heat transfer process becomes less and less irreversible as the temperature difference between the two bodies approaches zero. Then heat transfer through a differential temperature difference dT can be considered to be reversible. As dT approaches zero, the process can be reversed in direction (at least theoretically) without requiring any refrigeration.

- Notice that reversible heat transfer is a conceptual process and cannot be duplicated in the real world.

- The smaller the temperature difference between two bodies, the smaller the heat transfer rate will be.

- Any significant heat transfer through a small temperature difference requires a very large surface area and a very long time. Therefore, even though approaching reversible heat transfer is desirable from a thermodynamic point of view, it is impractical and not economically feasible.



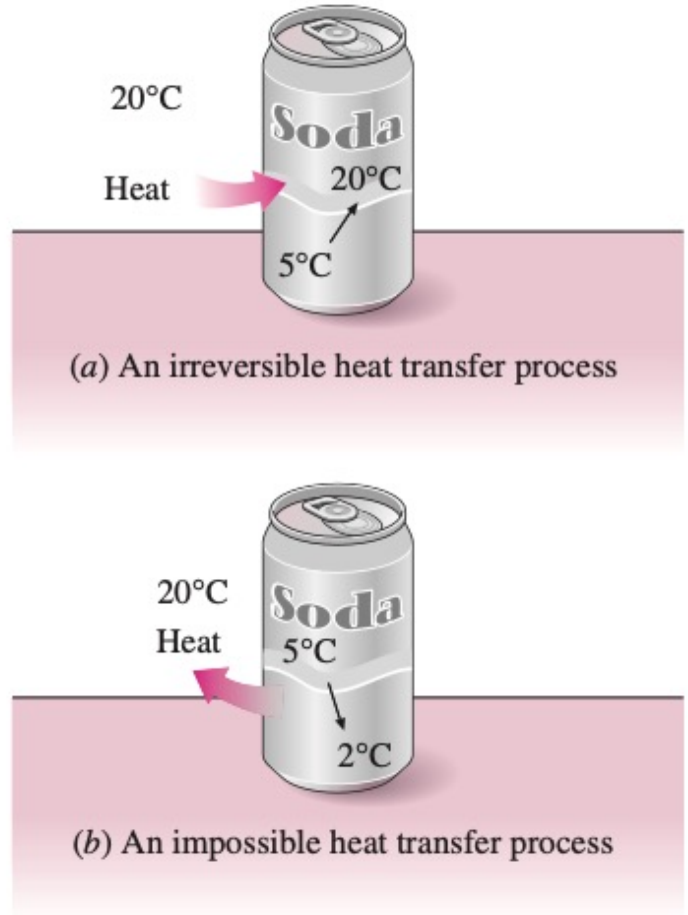
(*a*) Fast compression

(*b*) Fast expansion

(*c*) Unrestrained expansion

FIGURE 6–33

Irreversible compression and expansion processes.



(*a*) An irreversible heat transfer process

(*b*) An impossible heat transfer process

FIGURE 6–34

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

Internally and Externally Reversible Processes

- A typical process involves interactions between a system and its surroundings, and a reversible process involves no irreversibilities associated with either of them.

- A process is called **internally reversible** if no irreversibilities occur within the boundaries of the system during the process.

- During an internally reversible process, a system proceeds through a series of equilibrium states, and when the process is reversed, the system passes through exactly the same equilibrium states while returning to its initial state.

- That is, the paths of the forward and reverse processes coincide for an internally reversible process. **The quasi-equilibrium process is an example of an internally reversible process.**

- **A process is called externally reversible if no irreversibilities occur outside the system boundaries during the process. Heat transfer between a reservoir and a system is an externally reversible process if the outer surface of the system is at the temperature of the reservoir.**

- **A process is called totally reversible, or simply reversible, if it involves no irreversibilities within the system or its surroundings** (Fig. 6–35). A totally reversible process involves no heat transfer through a finite temperature difference, no nonquasi-equilibrium changes, and no friction or other dissipative effects.

- As an example, consider the transfer of heat to two identical systems that are undergoing a constant-pressure (thus constant-temperature) phase- change process, as shown in Fig. 6–36. Both processes are internally reversible, since both take place isothermally and both pass through exactly the same equilibrium states.

- The first process shown is externally reversible also, since heat transfer for this process takes place through an infinitesimal temperature difference dT. The second process, however, is externally irreversible, since it involves heat transfer through a finite temperature difference ΔT.

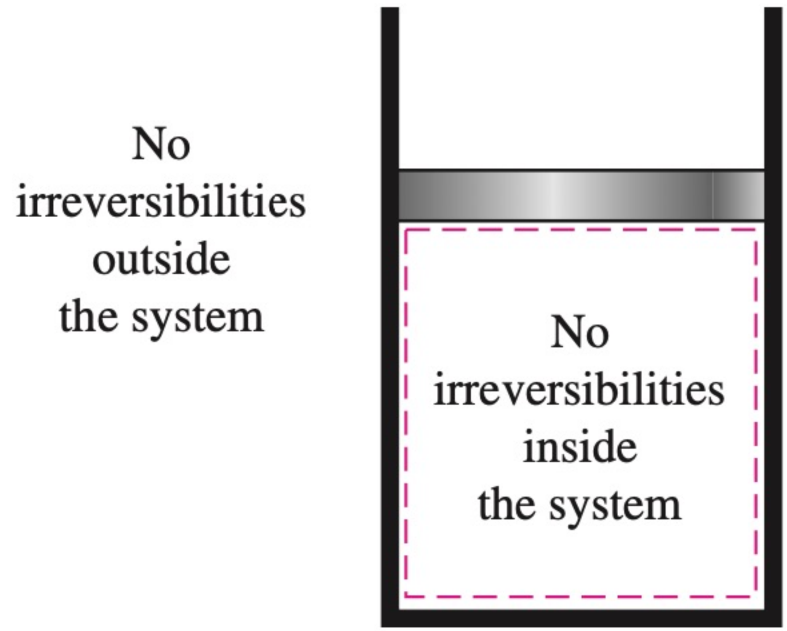


FIGURE 6–35

A reversible process involves no internal and external irreversibilities.

THE CARNOT CYCLE

- We mentioned earlier that heat engines are cyclic devices and that the working fluid of a heat engine returns to its initial state at the end of each cycle.
- Work is done by the working fluid during one part of the cycle and on the working fluid during another part.
- The difference between these two is the net work delivered by the heat engine. The efficiency of a heat-engine cycle greatly depends on how the individual processes that make up the cycle are executed.
- The net work, thus the cycle efficiency, can be maximized by using processes that require the least amount of work and deliver the most, that is, by using *reversible processes*.
- Therefore, it is no surprise that the most efficient cycles are reversible cycles, that is, cycles that consist entirely of reversible processes.
- Reversible cycles cannot be achieved in practice because the irreversibilities associated with each process cannot be eliminated.

THE CARNOT CYCLE

- However, reversible cycles provide upper limits on the performance of real cycles. Heat engines and refrigerators that work on reversible cycles serve as models to which actual heat engines and refrigerators can be compared.

- Reversible cycles also serve as starting points in the development of actual cycles and are modified as needed to meet certain requirements.

- Probably the best known reversible cycle is the **Carnot cycle,** first proposed in 1824 by French engineer Sadi Carnot. The theoretical heat engine that operates on the Carnot cycle is called the **Carnot heat engine.**

- **The Carnot cycle is composed of four reversible processes—two isothermal and two adiabatic—and it can be executed either in a closed or a steady-flow system**.

- Consider a closed system that consists of a gas contained in an adiabatic piston–cylinder device, as shown in Fig. 6–37. The insulation of the cylinder head is such that it may be removed to bring the cylinder into contact with reservoirs to provide heat transfer. The four reversible processes that make up the Carnot cycle are as follows:

- **Reversible Isothermal Expansion** (process 1-2, T_H =constant). Initially (state 1), the temperature of the gas is *TH* and the cylinder head is in close contact with a source at temperature T_H.

- The gas is allowed to expand slowly, doing work on the surroundings. As the gas expands, the temperature of the gas tends to decrease.

- But as soon as the temperature drops by an infinitesimal amount dT, some heat is transferred from the reservoir into the gas, raising the gas temperature to T_H.

- Thus, the gas temperature is kept constant at T_H. Since the temperature difference between the gas and the reservoir never exceeds a differential amount dT, this is a reversible heat transfer process.

- It continues until the piston reaches position 2. The amount of total heat transferred to the gas during this process is Q_H.

- **Reversible Adiabatic Expansion** (process 2-3, temperature drops from *TH* to *TL*). At state 2, the reservoir that was in contact with the cylinder head is removed and replaced by insulation so that the system becomes adiabatic.

- The gas continues to expand slowly, doing work on the surroundings until its temperature drops from T_H to T_L (state 3).

- The piston is assumed to be frictionless and the process to be quasi- equilibrium, so the process is reversible as well as adiabatic.

- **Reversible Isothermal Compression (process 3-4, T_L = constant). At state 3, the insulation at the cylinder head is removed, and the cylinder is brought into contact with a sink at temperature T_L.**

- Now the piston is pushed inward by an external force, doing work on the gas. As the gas is compressed, its temperature tends to rise.

- But as soon as it rises by an infinitesimal amount dT, heat is transferred from the gas to the sink, causing the gas temperature to drop to T_L.

- Thus, the gas temperature remains constant at T_L. Since the temperature difference between the gas and the sink never exceeds a differential amount dT, this is a reversible heat transfer process. It continues until the piston reaches state 4.

- The amount of heat rejected from the gas during this process is Q_L.

- **Reversible Adiabatic Compression** (process 4-1, temperature rises from *TL* to *TH*). State 4 is such that when the low-temperature reservoir is removed, the insulation is put back on the cylinder head, and the gas is compressed in a reversible manner, the gas returns to its initial state (state 1).

- The temperature rises from *TL* to *TH* during this reversible adiabatic compression process, which completes the cycle.

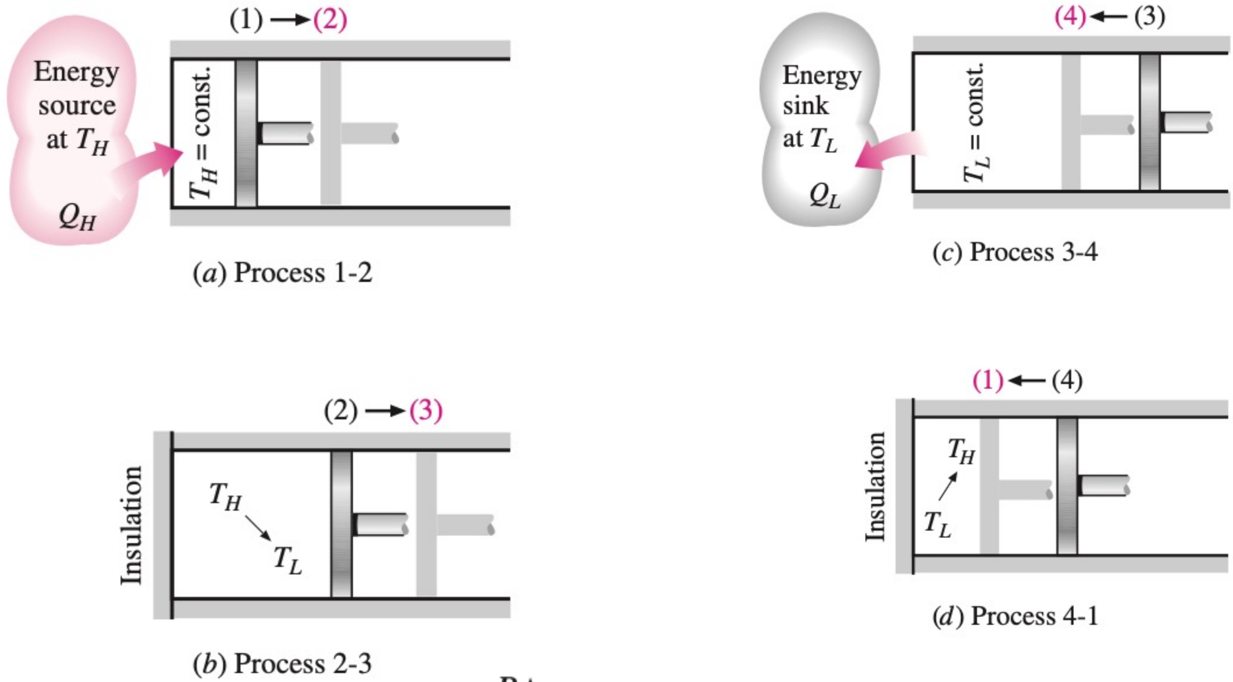


FIGURE 6–37

Execution of the Carnot cycle in a closed system.

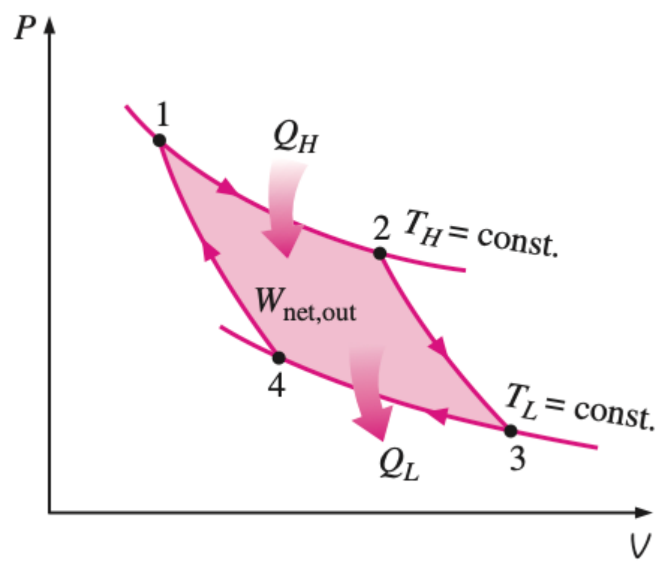


FIGURE 6–38

P-*V* diagram of the Carnot cycle.

- The *P*-V diagram of this cycle is shown in Fig. 6–38. Remembering that on a *P*-V diagram the area under the process curve represents the boundary work for quasi-equilibrium (internally reversible) processes, we see that the area under curve 1-2-3 is the work done by the gas during the expansion part of the cycle, and the area under curve 3-4-1 is the work done on the gas during the compression part of the cycle.

- The area enclosed by the path of the cycle (area 1-2-3-4-1) is the difference between these two and represents the net work done during the cycle.

- Notice that if we acted stingily and compressed the gas at state 3 adiabatically instead of isothermally in an effort *to save QL*, we would end up back at state 2, retracing the process path 3-2.

- By doing so we would save *QL*, but we would not be able to obtain any net work output from this engine.

- This illustrates once more the necessity of a heat engine exchanging heat with at least two reservoirs at different temperatures to operate in a cycle and pro- duce a net amount of work.

- The Carnot cycle can also be executed in a steady-flow system. It is dis- cussed in later chapters in conjunction with other power cycles.
- Being a reversible cycle, the Carnot cycle is the most efficient cycle oper- ating between two specified temperature limits.
- Even though the Carnot cycle cannot be achieved in reality, the efficiency of actual cycles can be improved by attempting to approximate the Carnot cycle more closely.

The Reversed Carnot Cycle

- **The Carnot heat-engine cycle just described is a totally reversible cycle.** Therefore, all the processes that comprise it can be *reversed*, in which case it becomes the **Carnot refrigeration cycle.**

- This time, the cycle remains exactly the same, except that the directions of any heat and work interactions are reversed: Heat in the amount of Q_L is absorbed from the low-temperature reservoir, heat in the amount of Q_H is rejected to a high-temperature reservoir, and a work input of $W_{net,in}$ is required to accomplish all this.

- The P-V diagram of the reversed Carnot cycle is the same as the one given for the Carnot cycle, except that the directions of the processes are reversed, as shown in Fig. 6–39.

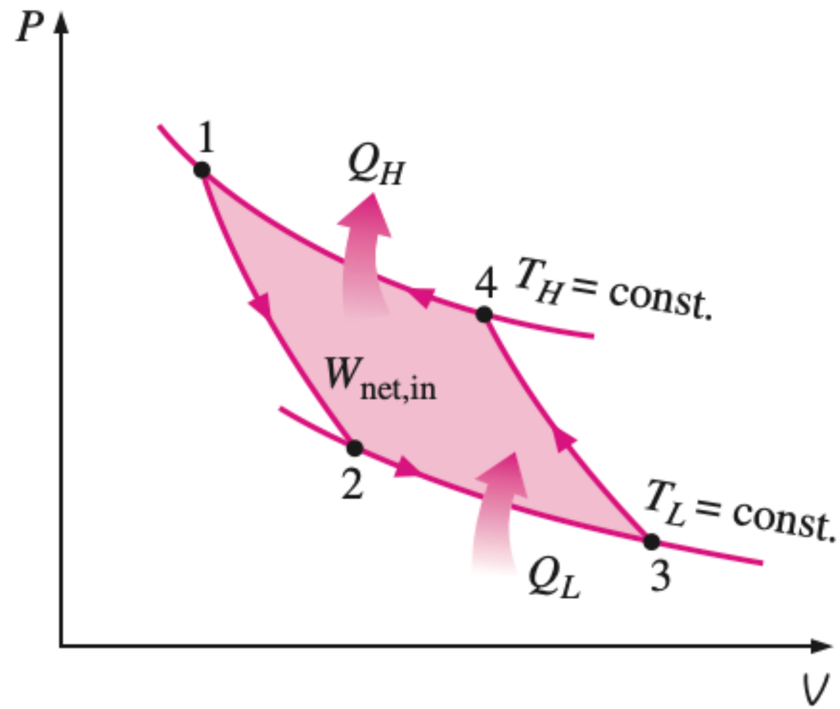


FIGURE 6–39

P-V diagram of the reversed Carnot cycle.

THE CARNOT PRINCIPLES

- **The second law of thermodynamics puts limits on the operation of cyclic devices as expressed by the Kelvin–Planck and Clausius statements.**

- **A heat engine cannot operate by exchanging heat with a single reservoir, and a refrigerator cannot operate without a net energy input from an external source.**

- **We can draw valuable conclusions from these statements. Two conclusions pertain to the thermal efficiency of reversible and irreversible (i.e., actual) heat engines, and they are known as the Carnot principles (Fig. 6–40), expressed as follows:**

1. **The efficiency of an irreversible heat engine is always less 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.**

- These two statements can be proved by demonstrating that the violation of either statement results in the violation of the second law of thermodynamics.

- To prove the first statement, consider two heat engines operating between the same reservoirs, as shown in Fig. 6–41.

- One engine is reversible and the other is irreversible. Now each engine is supplied with the same amount of heat Q_H. The amount of work produced by the reversible heat engine is

- *W*rev, and the amount produced by the irreversible one is W_{irrev}.

- In violation of the first Carnot principle, we assume that the irreversible heat engine is more efficient than the reversible one (that is, $\eta_{th,irrev}$ - $\eta_{th,rev}$) and thus delivers more work than the reversible one.

- Now let the reversible heat engine be reversed and operate as a refrigerator. This refrigerator will receive a work input of *W*rev and reject heat to the high-temperature reservoir.

- Since the refrigerator is rejecting heat in the amount of Q_H to the high- temperature reservoir and the irreversible heat engine is receiving the same amount of heat from this reservoir, the net heat exchange for this reservoir is zero.

- Thus, it could be eliminated by having the refrigerator discharge *QH* directly into the irreversible heat engine.

- Now considering the refrigerator and the irreversible engine together, we have an engine that produces a net work in the amount of $W_{irrev} - W_{rev}$

- while exchanging heat with a single reservoir—a violation of the Kelvin– Planck statement of the second law.

- Therefore, our initial assumption that $\eta_{th,irrevhth,rev}$ is incorrect. Then we conclude that no heat engine can be more efficient than a reversible heat engine operating between the same reservoirs.

- The second Carnot principle can also be proved in a similar manner. This time, let us replace the irreversible engine by another reversible engine that is more efficient and thus delivers more work than the first reversible engine.

- By following through the same reasoning, we end up having an engine that produces a net amount of work while exchanging heat with a single reservoir, which is a violation of the second law.

- Therefore, we conclude that no reversible heat engine can be more efficient than a reversible one operating between the same two reservoirs, regardless of how the cycle is completed or the kind of working fluid used.

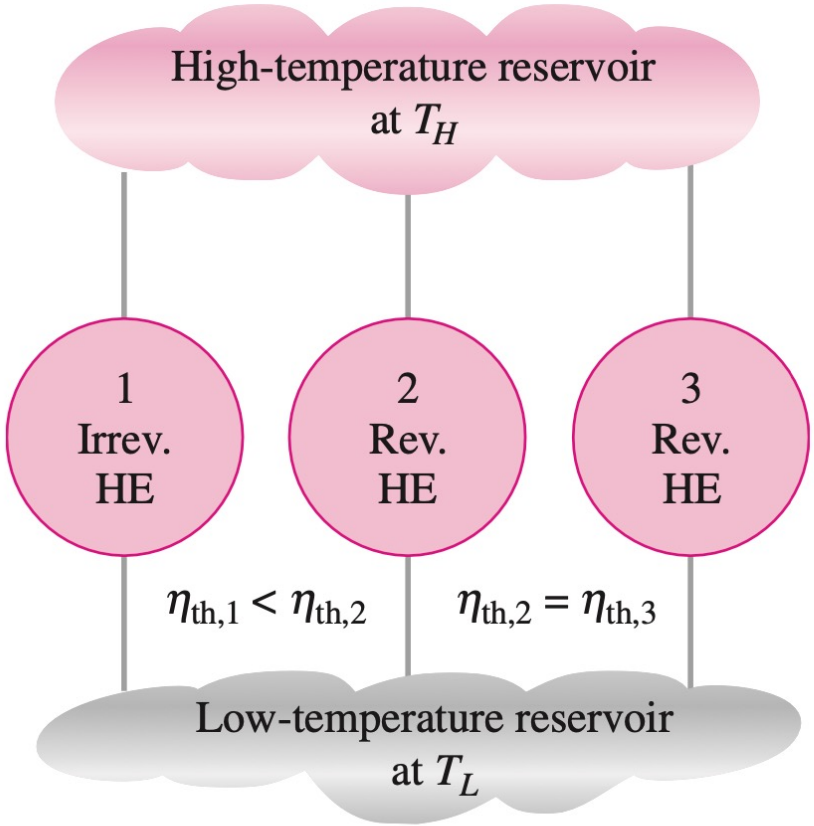


FIGURE 6–40

The Carnot principles.

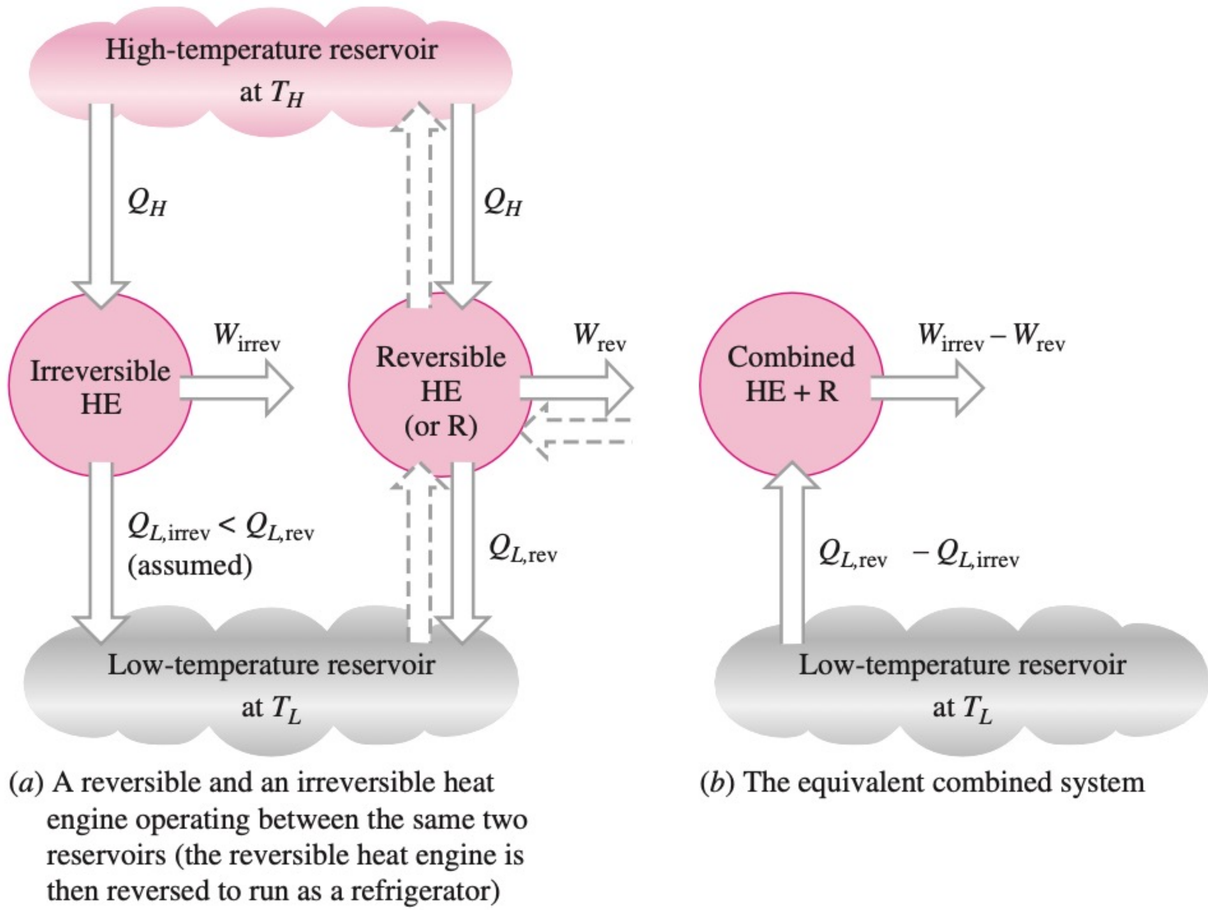


FIGURE 6–41

Proof of the first Carnot principle.

6–10 ▪ THE CARNOT HEAT ENGINE

The hypothetical heat engine that operates on the reversible Carnot cycle is called the **Carnot heat engine.** The thermal efficiency of any heat engine, reversible or irreversible, is given by Eq. 6–6 as

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

where Q_H is heat transferred to the heat engine from a high-temperature reservoir at T_H, and Q_L is heat rejected to a low-temperature reservoir at T_L. For reversible heat engines, the heat transfer ratio in the above relation can be replaced by the ratio of the absolute temperatures of the two reservoirs, as given by Eq. 6–16. Then the efficiency of a Carnot engine, or any reversible heat engine, becomes

$$\eta_{\text{th,rev}} = 1 - \frac{T_L}{T_H} \qquad \textbf{(6–18)}$$

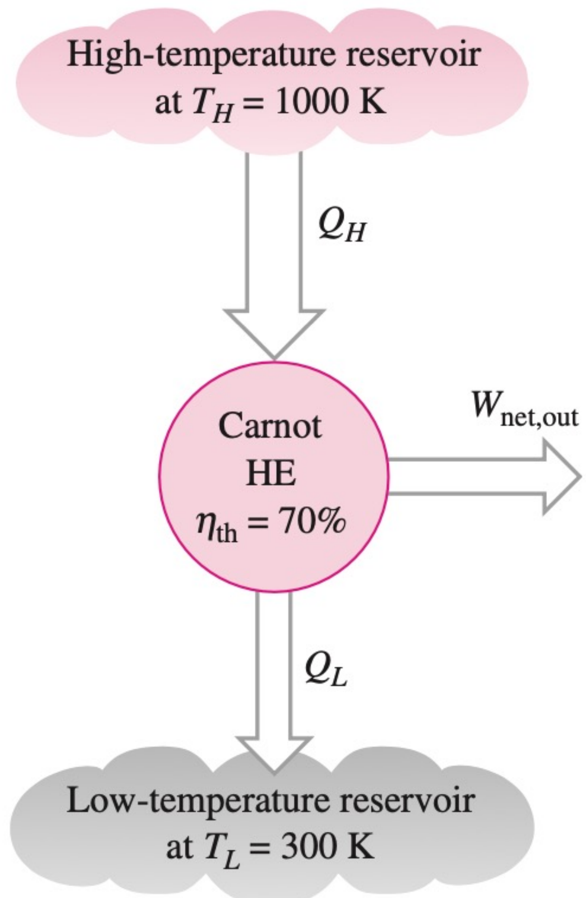


FIGURE 6–46

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

- **This relation is often referred to as the Carnot efficiency, since the Carnot heat engine is the best known reversible engine.** ***This is the highest efficiency a heat engine operating between the two thermal energy reservoirs at temperatures T_L and T_H can have*** **(Fig. 6–46).**

- All irreversible (i.e., actual) heat engines operating between these temperature limits (T_L and T_H) have lower efficiencies.

- An actual heat engine cannot reach this maximum theoretical efficiency value because it is impossible to completely eliminate all the irreversibilities associated with the actual cycle.

- Note that T_L and T_H in Eq. 6–18 are *absolute temperatures*. Using °C or °F for temperatures in this relation gives results grossly in error.

- The thermal efficiencies of actual and reversible heat engines operating between the same temperature limits compare as follows (Fig. 6–47):

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

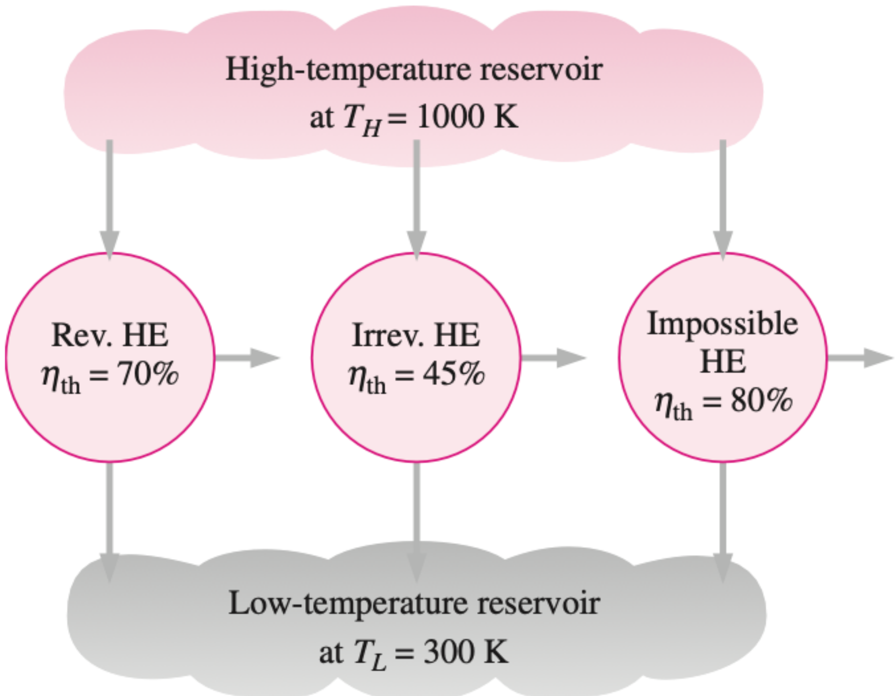


FIGURE 6–47

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

- Most work-producing devices (heat engines) in operation today have efficiencies under 40 percent, which appear low relative to 100 percent.

- However, when the performance of actual heat engines is assessed, the efficiencies should not be compared to 100 percent; instead, they should be compared to the efficiency of a reversible heat engine operating between the same temperature limits—because this is the true theoretical upper limit for the efficiency, not 100 percent.

- The maximum efficiency of a steam power plant operating between T_H = 1000 K and T_L = 300 K is 70 percent, as determined from Eq. 6–18. Compared with this value, an actual efficiency of 40 percent does not seem so bad, even though there is still plenty of room for improvement.

- It is obvious from Eq. 6–18 that the efficiency of a Carnot heat engine increases as *TH* is increased, or as *TL* is decreased. This is to be expected since as *TL* decreases, so does the amount of heat rejected, and as *TL* approaches zero, the Carnot efficiency approaches unity.

- This is also true for actual heat engines. *The thermal efficiency of actual heat engines can be maximized by supplying heat to the engine at the highest possible tempera- ture* (limited by material strength) *and rejecting heat from the engine at the lowest possible temperature* (limited by the temperature of the cooling medium such as rivers, lakes, or the atmosphere).

EXAMPLE 6–5 **Analysis of a Carnot Heat Engine**

A Carnot heat engine, shown in Fig. 6–48, 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 (*a*) the thermal efficiency of this Carnot engine and (*b*) the amount of heat rejected to the sink per cycle.

Solution The heat supplied to a Carnot heat engine is given. The thermal efficiency and the heat rejected are to be determined.

Analysis (*a*) The Carnot heat engine is a reversible heat engine, and so its efficiency can be determined from Eq. 6–18 to be

$$\eta_{\text{th},C} = \eta_{\text{th,rev}} = 1 - \frac{T_L}{T_H} = 1 - \frac{(30 + 273)\text{ K}}{(652 + 273)\text{ K}} = \mathbf{0.672}$$

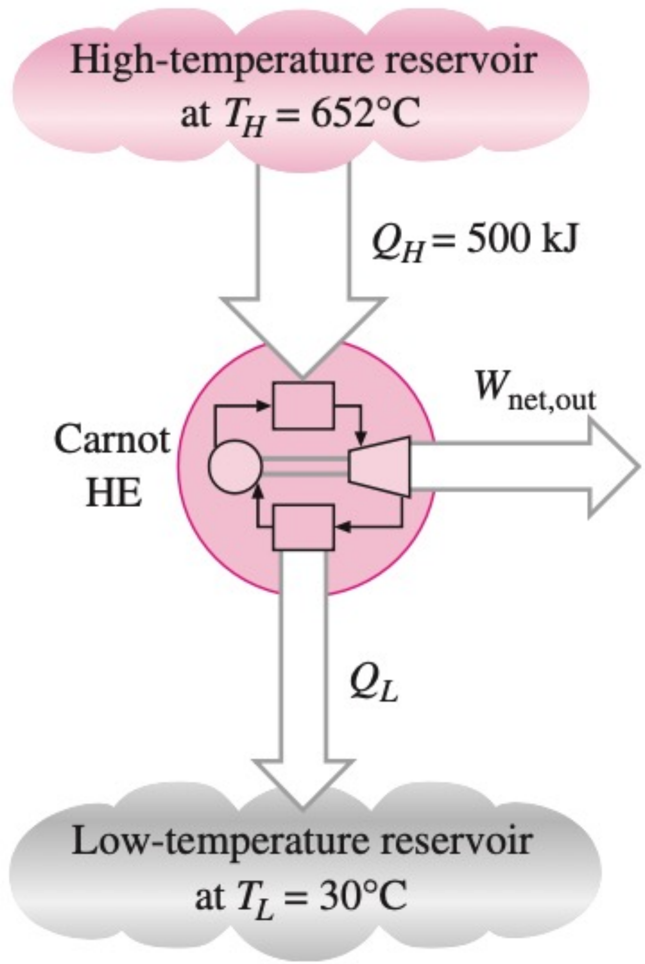


FIGURE 6–48

Schematic for Example 6–5.

That is, this Carnot heat engine converts 67.2 percent of the heat it receives to work.

(*b*) The amount of heat rejected Q_L by this reversible heat engine is easily determined from Eq. 6–16 to be

$$Q_{L,\text{rev}} = \frac{T_L}{T_H} Q_{H,\text{rev}} = \frac{(30 + 273)\text{ K}}{(652 + 273)\text{ K}}(500\text{ kJ}) = \mathbf{164\text{ kJ}}$$

Discussion Note that this Carnot heat engine rejects to a low-temperature sink 164 kJ of the 500 kJ of heat it receives during each cycle.

6–11 ▪ THE CARNOT REFRIGERATOR AND HEAT PUMP

A refrigerator or a heat pump that operates on the reversed Carnot cycle is called a **Carnot refrigerator,** or a **Carnot heat pump.** The coefficient of performance of any refrigerator or heat pump, reversible or irreversible, is given by Eqs. 6–9 and 6–11 as

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

where Q_L is the amount of heat absorbed from the low-temperature medium and Q_H is the amount of heat rejected to the high-temperature medium. The COPs of all reversible refrigerators or heat pumps can be determined by replacing the heat transfer ratios in the above relations by the ratios of the absolute temperatures of the high- and low-temperature reservoirs, as expressed by Eq. 6–16. Then the COP relations for reversible refrigerators and heat pumps become

$$\text{COP}_\text{R,rev} = \frac{1}{T_H/T_L - 1} \tag{6–20}$$

and

$$\text{COP}_\text{HP,rev} = \frac{1}{1 - T_L/T_H} \tag{6–21}$$

- ***These are the highest coefficients of performance that a refrigerator or a heat pump operating between the temperature limits of T_L and T_H can have.***

- All actual refrigerators or heat pumps operating between these temperature limits (T_L and T_H) have lower coefficients of performance (Fig. 6–51).

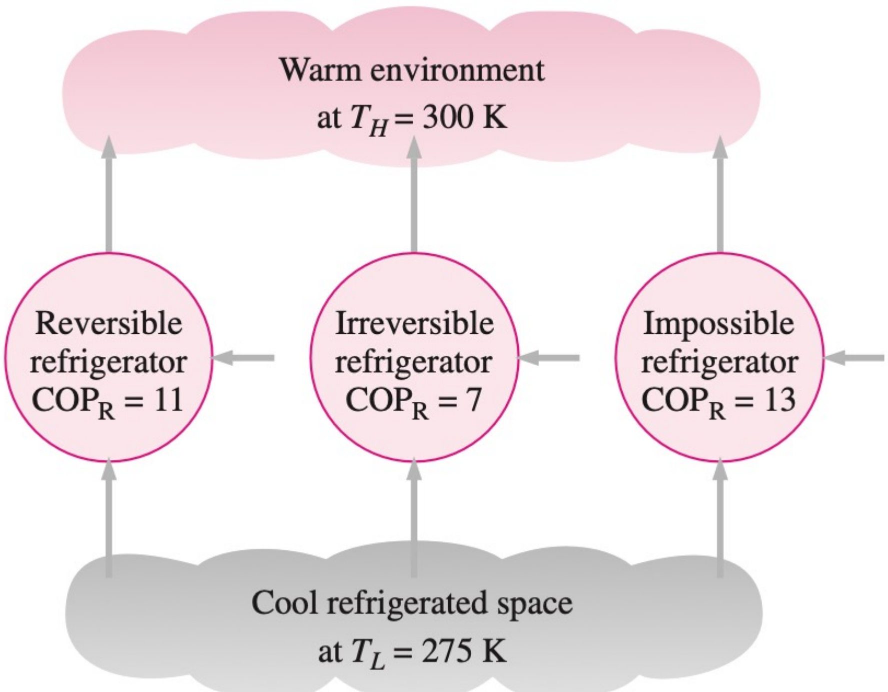


FIGURE 6–51
No refrigerator can have a higher COP than a reversible refrigerator operating between the same temperature limits.

The coefficients of performance of actual and reversible refrigerators operating between the same temperature limits can be compared as follows:

$$COP_R \begin{cases} < COP_{R,rev} & \text{irreversible refrigerator} \\ = COP_{R,rev} & \text{reversible refrigerator} \\ > COP_{R,rev} & \text{impossible refrigerator} \end{cases} \qquad \textbf{(6–22)}$$

A similar relation can be obtained for heat pumps by replacing all COP_R's in Eq. 6–22 by COP_{HP}.

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.

As a final note, the COPs of both the refrigerators and the heat pumps decrease as T_L decreases. That is, it requires more work to absorb heat from lower-temperature media. As the temperature of the refrigerated space approaches zero, the amount of work required to produce a finite amount of refrigeration approaches infinity and COP_R approaches zero.

EXAMPLE 6–6 A Questionable Claim for a Refrigerator

An inventor claims to have developed a refrigerator that maintains the refrigerated space at 35°F while operating in a room where the temperature is 75°F and that has a COP of 13.5. Is this claim reasonable?

Solution An extraordinary claim made for the performance of a refrigerator is to be evaluated.

Assumptions Steady operating conditions exist.

Analysis The performance of this refrigerator (shown in Fig. 6–52) can be evaluated by comparing it with a reversible refrigerator operating between the same temperature limits:

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

$$= \frac{1}{(75 + 460\ \mathrm{R})/(35 + 460\ \mathrm{R}) - 1} = 12.4$$

Discussion This is the highest COP a refrigerator can have when absorbing heat from a cool medium at 35°F and rejecting it to a warmer medium at 75°F. Since the COP claimed by the inventor is above this maximum value, **the claim is *false*.**

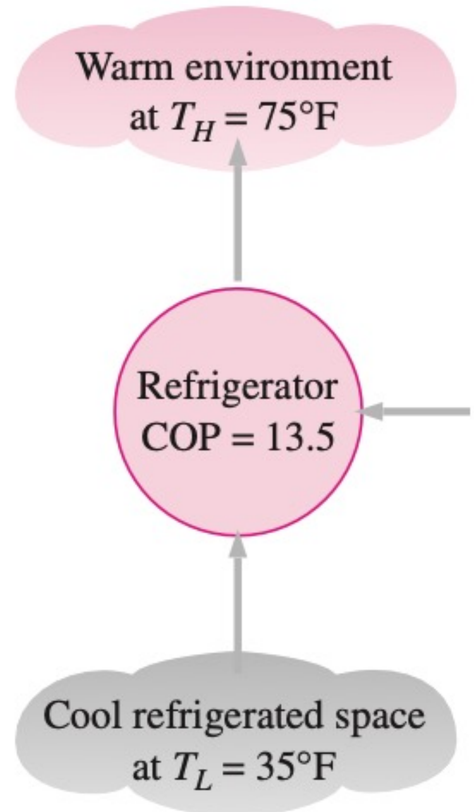


FIGURE 6–52

Schematic for Example 6–6.

EXAMPLE 6–7 Heating a House by a Carnot Heat Pump

A heat pump is to be used to heat a house during the winter, as shown in Fig. 6–53. The house is to be maintained at 21°C at all times. The house is estimated to be losing heat at a rate of 135,000 kJ/h when the outside temperature drops to −5°C. Determine the minimum power required to drive this heat pump.

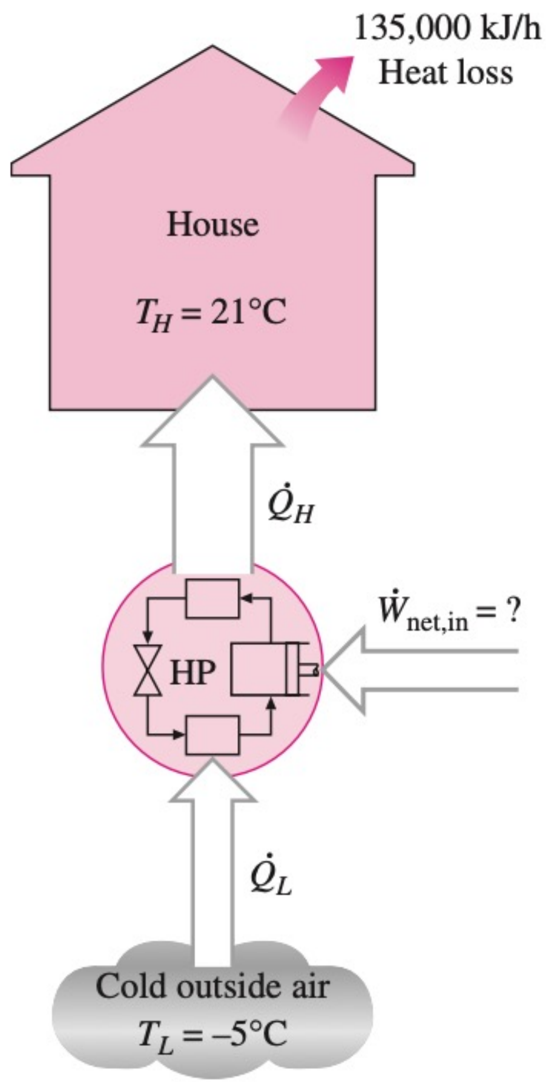


FIGURE 6–53

Schematic for Example 6–7.

Solution A heat pump maintains a house at a constant temperature. The required minimum power input to the heat pump is to be determined.

Assumptions Steady operating conditions exist.

Analysis The heat pump must supply heat to the house at a rate of Q_H = 135,000 kJ/h = 37.5 kW. The power requirements are minimum when a reversible heat pump is used to do the job. The COP of a reversible heat pump operating between the house and the outside air is

$$\mathrm{COP}_{\mathrm{HP,rev}} = \frac{1}{1 - T_L/T_H} = \frac{1}{1 - (-5 + 273\ \mathrm{K})/(21 + 273\ \mathrm{K})} = 11.3$$

Then the required power input to this reversible heat pump becomes

$$\dot{W}_{\mathrm{net,in}} = \frac{Q_H}{\mathrm{COP}_{\mathrm{HP}}} = \frac{37.5\ \mathrm{kW}}{11.3} = \mathbf{3.32\ kW}$$

Discussion This reversible heat pump can meet the heating requirements of this house by consuming electric power at a rate of 3.32 kW only. If this house were to be heated by electric resistance heaters instead, the power consumption would jump up 11.3 times to 37.5 kW. This is because in resistance heaters the electric energy is converted to heat at a one-to-one ratio. With a heat pump, however, energy is absorbed from the outside and carried to the inside using a refrigeration cycle that consumes only 3.32 kW. Notice that the heat pump does not create energy. It merely transports it from one medium (the cold outdoors) to another (the warm indoors).