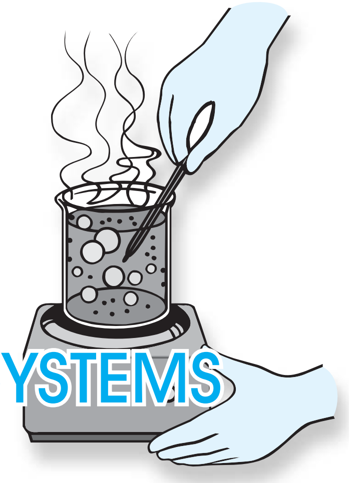
5.4 ENERGY IN THERMAL SYSTEMS



Objectives

- Define the internal energy of a system.
- Describe two ways you can change a system's internal energy.
- Explain the first law of thermodynamics. Use the first law to solve problems involving internal energy, heat, and work.
- Describe the operation of a heat engine and a refrigerator.
- Explain the second law of thermodynamics. Describe processes that are prohibited by the second law.
- Explain the differences between the Celsius and Kelvin temperature scales.
- Calculate the Carnot efficiency of a heat engine.

INTERNET *connection*

To find out more about energy in thermal systems, follow the links at **www.learningincontext.com.**

In Section 1.4 you learned that the temperature of a body is determined by its thermal energy. Thermal energy is the total kinetic energy of the random motion of the atoms or molecules that make up the body. This microscopic, random kinetic energy is not the same as the kinetic energy the body has as a whole. A moving body has a net velocity. The kinetic energy of this *ordered motion* is equal to $\frac{1}{2}mv^2$, where m and v are the mass and speed of the entire body.

Thermal energy is due to *random motion* of the atoms and molecules that make up the body. There is no net velocity of random motion. If you could "freeze" the particles' motion at one instant and count the number of particles moving in any given direction, you would count the same number moving in the opposite direction. Each particle in the body has a kinetic energy of random motion, equal to $\frac{1}{2}mv^2$, where m and v are the mass and speed of the particle. This speed changes frequently, as the particle interacts with other particles of the body.

In addition to moving in random translational motion, molecules of a gas can rotate and vibrate. All three modes are illustrated in Figure 5.28 for a diatomic gas. A molecule of a diatomic gas consists of two atoms bound together. Oxygen is a diatomic gas. A molecule of oxygen is written with the symbol O_2, to indicate that two oxygen atoms are bound together in a molecule. In a container of oxygen gas, the molecules have translational, rotational, and vibrational motion. But the temperature of the oxygen is determined by only the translational kinetic energy.

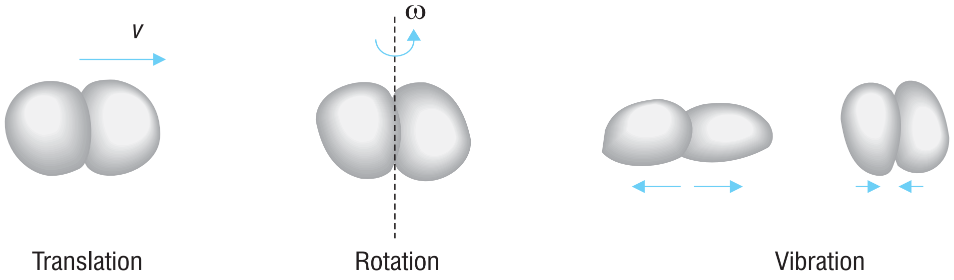


Figure 5.28
Gas molecules can translate, rotate, and vibrate. But only the kinetic energy of translational motion affects the temperature of the gas.

The particles of a liquid or solid are much closer together, and electrical forces limit their motions. In a solid, atoms and molecules are held in place by electrical forces and they vibrate about the fixed positions. In a liquid, the particles can slide past one another but their speeds are affected by electrical interactions with other particles. In any material, when atomic and molecular charge is moved in an electric field, the particles' energy can be stored as electric potential energy.

Internal Energy

On a microscopic scale, the particles of a body—whether it is a solid, liquid, gas, or plasma—are in constant random motion. As particles interact, the kinetic energy and potential energy of any given particle change. But, for an isolated body, the sum of the kinetic and potential energies of all the particles does not change. This total energy is called the **internal energy** of the body.

A body's internal energy depends on its material composition, its mass, its temperature, and its physical state (solid, liquid, gas, or plasma). Internal energy can be transferred from one body to another body if the bodies have different temperatures. Internal energy transferred because of a temperature difference is heat.

There is another way of changing a body's internal energy besides heat transfer. You can see this method with a simple demonstration. Place your hands together. If your right hand is the same temperature as your left hand, there is no heat transfer between them. So you cannot increase the internal energy of either hand with heat transfer. Now rub your hands together vigorously. You have increased the internal energy and temperature of your hands by doing work using the force of friction.

Figure 5.29
Work can be converted into internal energy.

Work done by frictional forces is converted into internal energy. Other forms of energy and work also can be converted into internal energy. For example, an electric stove uses resistance in its heating elements to convert electrical energy into internal energy. If you have ever used a hand pump to inflate a basketball, you have probably noticed that the pump gets hot. Some of this internal energy comes from friction, but most comes from work done by the piston on the air in the cylinder.

So a system's internal energy can be increased by adding heat or by doing work on the system. The reverse is also true—a system's internal energy can be decreased by removing heat or by the system doing work. The science dealing with the relationships between internal energy, heat, and work is called **thermodynamics**.

The First Law of Thermodynamics

The law of conservation of energy says that energy cannot be created or destroyed, but it can be changed into other forms. This law applied to thermal systems is called the **first law of thermodynamics**. In equation form, the first law says that a change in a system's internal energy is balanced by heat Q input to the system and work W done by the system. We use the variable U to represent internal energy.

$$\text{Change in internal energy of a system} = \text{net heat input to the system} - \text{work done by the system}$$

$$\Delta U = Q - W$$

When you use the first law to solve problems, you should first identify the system to which you are applying the law. The system should be a well-defined set of atoms, molecules, particles, or objects. For example, a system could be the air and fuel mixture in a car engine's cylinder, the cytoplasm inside a single biological cell, or the entire mass of an exploding star.

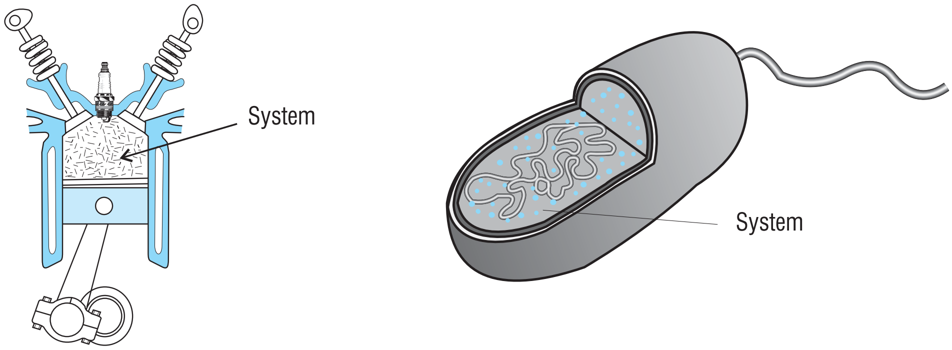


Figure 5.30
A system is a well-defined set of atoms, molecules, particles, or objects.

When you have defined the system, be careful to use the right sign for each term in the equation for the first law. Energy can enter or leave the system through heat and work. Heat is *positive* if it *enters* the system and negative if it leaves. But work is subtracted from heat. This is because, by convention, work is *positive* when the system *does* the work (energy *leaves* the system in this case, so you subtract energy). Work is *negative* when work *is done on* the system (energy *enters* the system in this case, so you add energy). These conventions arose at the beginning of the field of thermodynamics, when the laws were applied to engines. The goals of scientists and engineers were to maximize the work done by engines and to minimize the heat (and therefore cost) that must be provided.

The signs of internal energy, heat, and work are illustrated in Figure 5.31. The figure shows two ways of increasing the internal energy of air inside a cylinder—with heat transfer and with work. In each case, the system is the air inside the cylinder. An increase in internal energy means the change in internal energy is positive.

In Figure 5.31a, the cylinder is fitted with a lid. The lid does not move, so the system does not change volume, and can do no work. Suppose heat is added to the air, by placing the cylinder in contact with a high-temperature object like a stove burner. Heat enters the system, and is positive. The first law of thermodynamics for this case is

$$\Delta U = Q - 0 = Q$$

When heat is added to the system, Q is positive and the system's internal energy increases.

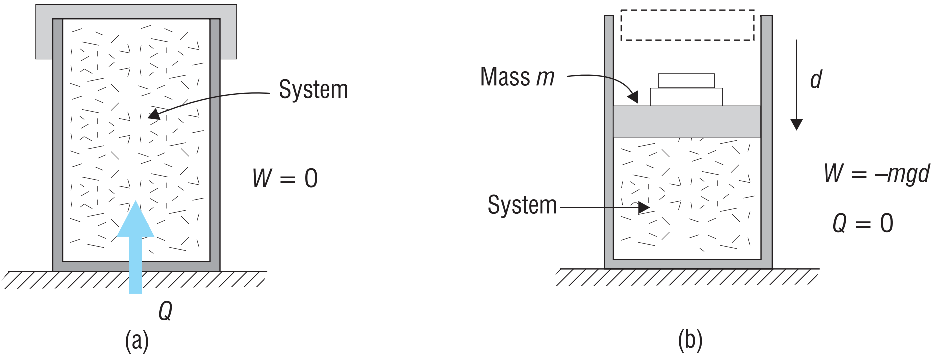


Figure 5.31
A system's internal energy can be increased by adding heat or by doing work on the system.

In Figure 5.31b, no heat is allowed to enter or leave the system. The cylinder is fitted with a movable, friction-free piston, which is forced downward by placing weights on top of the piston. In this case, the work done by the system is negative—work is done on the system. (If the total mass of the piston and added weights is m and the piston moves a distance d, the work done by gravity is mgd. The work done by the system is $-mgd$.)

A process in which there is no heat transfer to or from a system is called an **adiabatic** process. There are two ways of doing work adiabatically—you can isolate the system from its surroundings (with insulation), or you can do the work quickly enough that there is no time for heat transfer to take place. The first law of thermodynamics for an adiabatic process is

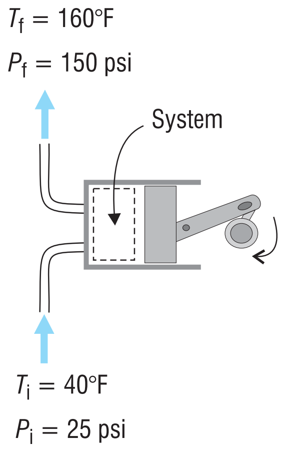
$$\Delta U = 0 - W = -W$$

When work is done on the system, as in Figure 5.31b, W is negative and the system's internal energy increases.

Can you explain how to *decrease* the internal energy of the system in Figure 5.31a, using only heat transfer? Can you explain how to *decrease* the internal energy of the system in Figure 5.31b, using only work?

Example 5.16 The First Law for a Compressor

A refrigerator's compressor has a cylinder fitted with a piston. The cylinder fills with refrigerant gas, and the piston compresses the gas to increase its temperature and pressure. During the compression process, 0.015 Btu of heat is removed from the gas. The internal energy increases by 0.036 Btu. How much work is done on the gas by the compressor?



Solution: The system is the gas in the cylinder. Use the first law of thermodynamics.

$$\begin{array}{c}\text{Change in internal}\\\text{energy of a system}\end{array} = \begin{array}{c}\text{net heat input}\\\text{to the system}\end{array} - \begin{array}{c}\text{work done by}\\\text{the system}\end{array}$$

$$\Delta U = Q - W$$

Since the internal energy of the system increases, the change in internal energy is positive. Since heat is removed from the system, the net heat input is negative.

$$0.036 \text{ Btu} = -0.015 \text{ Btu} - W$$

$$W = (-0.036 - 0.015) \text{ Btu} = -0.051 \text{ Btu}$$

The work is negative because work is done on the system. The compressor does 0.051 Btu of work on the gas.

Heat Engines

A device that converts thermal energy into mechanical energy is called a **heat engine**. Examples are automobile and truck engines whose energy source is the burning of gasoline or diesel fuel, steam turbines whose energy source is the burning of fossil fuel (coal, oil, or natural gas) or nuclear reactions, the space shuttle main engine whose energy source is the chemical reaction between hydrogen and oxygen, and your own body whose energy source is the food you eat.

Every heat engine:

- Absorbs thermal energy from a high-temperature source.
- Converts some of the thermal energy into work.
- Discards the remaining thermal energy into a low-temperature "sink."

The sources and sinks of thermal energy are called reservoirs. The low-temperature reservoir is usually the Earth, the Earth's atmosphere, or a body of water on the Earth's surface.

The first law of thermodynamics applies to all heat engines. Many engines operate continuously or in a cycle, where the internal energy and temperature are constant. For example, your car's engine operates at a constant temperature after a "warm-up" period. When the internal energy does not change, the first law says:

$$\begin{array}{c}\text{Net heat input}\\ \text{to the system}\end{array} = \begin{array}{c}\text{work done by}\\ \text{the system}\end{array}$$

$$Q = W$$

The net heat input is the amount of heat the engine absorbs from the high-temperature reservoir minus the amount of heat the engine discards to the low-temperature reservoir. Figure 5.32 shows the balance of heat and work required by the first law.

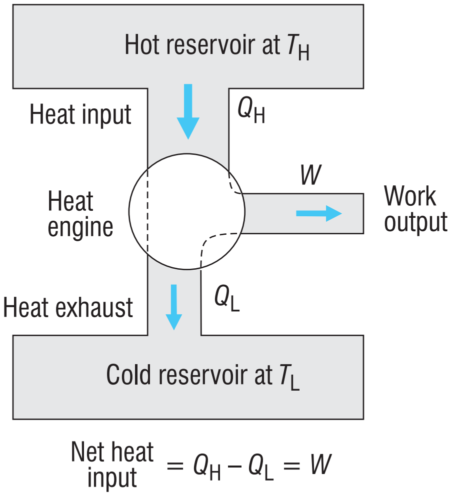


Figure 5.32
When there is no change in internal energy, the work done by an engine is the difference between the amount of heat absorbed and the amount of heat discarded.

A four-stroke gasoline engine is an example of a heat engine that operates in a cycle. The cycle is illustrated in Figure 5.33 on the next page. The high-temperature reservoir is the burning fuel-air mixture. Heat is absorbed by the engine from this reservoir. Heat is discarded when hot exhaust gases are released to the atmosphere and also when heat is transferred to the cooling system. Coolant flows around the outside of each cylinder, where it is heated, and then flows to the radiator. In the radiator, heat is removed from the coolant and deposited into the atmosphere. The net heat input to the engine is the amount of heat absorbed minus the amount discarded. The work done by the engine equals the net heat input.

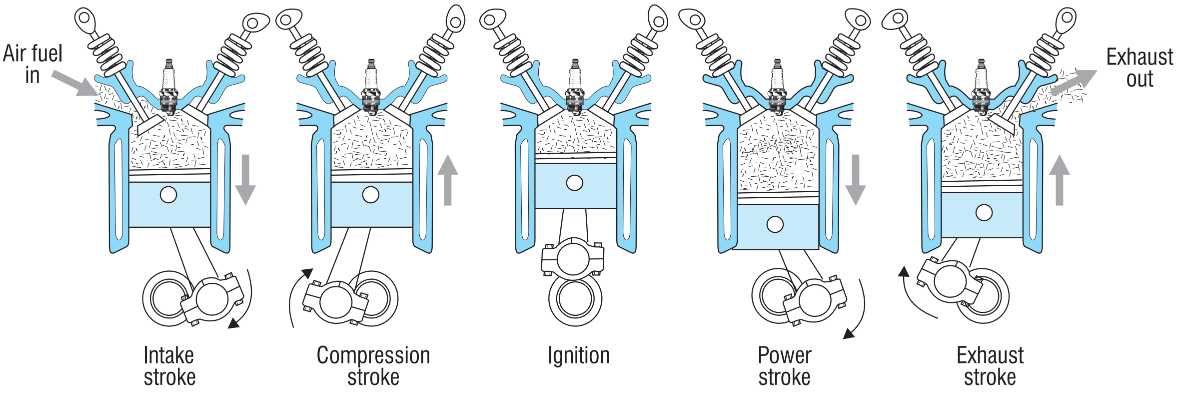


Figure 5.33
A cycle for one cylinder of a four-stroke gasoline engine.
A car engine usually has four, six, or eight of these cylinders.

But in a car or truck, the work done by the engine is not the work done to turn the wheels. Some of the engine's work must be used to overcome friction. Some must be used to keep the engine operating (moving gas into and out of cylinders and compressing gas). And some must be used to operate equipment (for example, air-conditioning, electrical generator, coolant pump, power steering). Typically, 60%–70% of the engine work is left over to cause motion in a car's transmission.

Refrigerators and Heat Pumps

A refrigerator operates in a cycle that is the reverse of the heat engine. A heat engine absorbs heat from a hot reservoir, exhausts heat to a cold reservoir, and provides mechanical work output. A refrigerator absorbs heat from a cold reservoir (the inside storage volume of the refrigerator) and exhausts heat to a hot reservoir (the outside of the storage volume). Mechanical work must be done on a *working fluid* in the refrigerator as input energy to "push" the heat from a cold to a hot reservoir.

Figure 5.34 shows the balance of heat and work required by the first law of thermodynamics for a refrigerator. The net heat input ($Q_L - Q_H$) is negative because $Q_L < Q_H$. Therefore, the work done by the refrigerator is also negative.

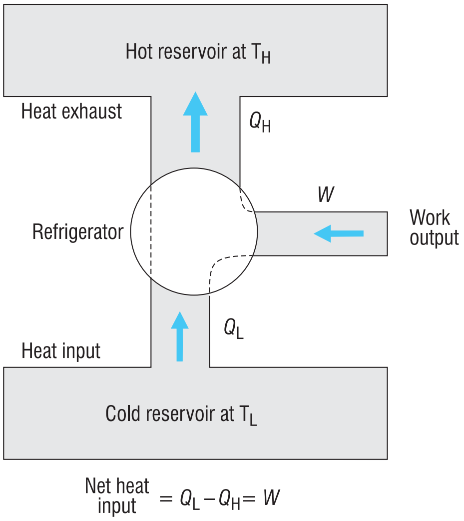


Figure 5.34

A refrigerator absorbs heat from a low-temperature reservoir and exhausts heat to a high-temperature reservoir. The difference between the heat absorbed and the heat exhausted is negative. This is the energy that must be supplied, as mechanical work, to allow heat to flow in the reverse direction.

How does a refrigerator move heat from a cold region to a hot region? A refrigerator is a closed system that uses a working fluid called the *refrigerant* to absorb and release heat, and to absorb energy as work. The refrigerant is usually a material such as ammonia, methyl chloride, a chlorofluorocarbon (being phased out due to environmental concerns), or a hydrochlorofluorocarbon. A refrigerator cycle is shown schematically in Figure 5.35. At some points in the cycle the refrigerant is a gas, at others it is a liquid, and at some points it exists in both states.

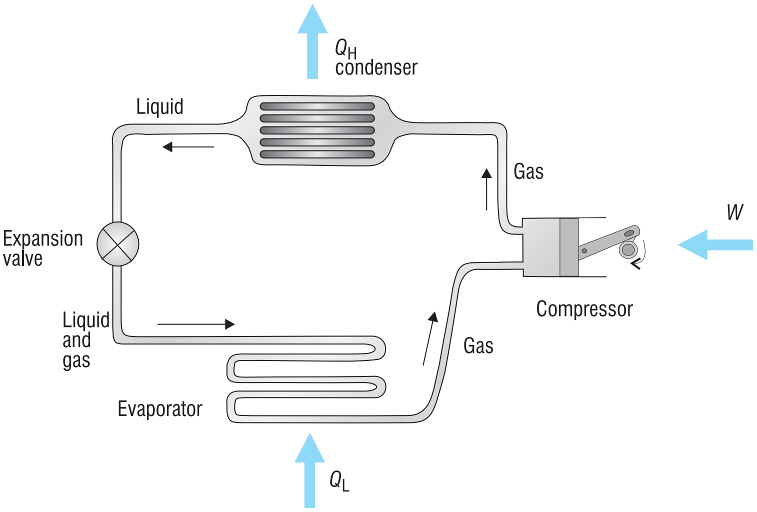


Figure 5.35

A refrigerator cycle. Heat enters and leaves the refrigerant when it changes phase in the condenser and evaporator. The compressor does work on the refrigerant.

There are four major components of a refrigerator. These components control the temperature, pressure, and volume of the refrigerant and its ability to absorb and release heat. The refrigerant enters the *compressor* as a low-pressure gas. The compressor has a piston that does work on the refrigerant in a cylinder. When the gas is compressed, its temperature and pressure increase.

From the compressor, the refrigerant flows into a *condenser*, where it is cooled and undergoes a change of phase, from gas to liquid. This phase change is called condensation, and it releases thermal energy equal to the refrigerant's heat of vaporization. The heat released is Q_H. This heat is transferred away from the condenser and to the high-temperature reservoir using air- or water-cooling of the condenser.

The refrigerant leaves the condenser as a high-pressure liquid. The pressure is decreased as the liquid flows through an *expansion valve*. On the low-pressure side of the expansion valve, some of the liquid becomes gas.

The remaining liquid is vaporized in an *evaporator*. To change phase from liquid to gas, the refrigerant absorbs thermal energy equal to the heat of vaporization. The heat absorbed is Q_L. This heat is transferred to the evaporator from the low-temperature reservoir, which is the refrigerated storage volume. From the evaporator, the refrigerant reenters the compressor.

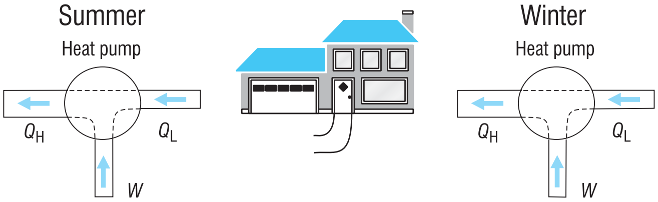


Figure 5.36
A heat pump acts as an air conditioner in the summer and a heater in the winter.

A *heat pump* is a refrigeration system that acts as an air conditioner in summer by extracting heat from the interior of a house and exhausting it to the warmer outdoors. In winter, the system reverses and acts as a heater, by taking heat from the cold outdoors and delivering it to the inside of the house. In both cases, mechanical work is done on the heat pump's refrigerant in order to satisfy the first law of thermodynamics.

Example 5.17 Heat Flow Rate Out of a Condenser

In a hospital's air-conditioning system, refrigerant is circulated through a refrigeration cycle at a rate of 110 kg/h. In the condenser, the refrigerant changes phase from gas to liquid at a constant temperature of 54°C. The heat of vaporization of the refrigerant at this temperature is 31.02 cal/g.

(a) Does the internal energy of the refrigerant in the condenser increase or decrease?

(b) At what rate is heat transferred out of the condenser in this air-conditioning system?

Solution: The system is the refrigerant in the condenser.

(a) Let Q_H represent the net heat input. Since no work is done in the condenser, the first law of thermodynamics is:

$$\Delta U = Q_H - W = Q_H$$

The heat of vaporization H_v is the amount of energy required to vaporize one gram of the refrigerant. This is also the amount of energy *released* when one gram of the refrigerant *condenses*. Since energy is released from the system, the net heat input is negative. If the mass of refrigerant is m, the net heat input is:

$$Q_H = -mH_v$$

Therefore, the change in internal energy is negative. The internal energy of refrigerant in the condenser decreases.

(b) In this problem, mass flow rate is given and heat flow rate is to be calculated. To obtain these rates, divide both sides of the equation above by a time interval Δt.

$$\frac{Q_H}{\Delta t} = -\frac{m}{\Delta t} H_v$$

Remember that the mass flow rate is $\dot{m} = \frac{m}{\Delta t}$ and the heat flow rate is $\dot{Q}_H = \frac{Q_H}{\Delta t}$. So you can write the equation as

$$\dot{Q}_H = -\dot{m} H_v$$

Substitute the given values for mass flow rate and heat of vaporization:

$$\dot{Q}_H = -\left(110 \frac{\text{kg}}{\text{h}}\right)\left(31.02 \frac{\text{cal}}{\text{g}}\right)\left(1000 \frac{\text{g}}{\text{kg}}\right)$$

$$\dot{Q}_H = -3.41 \times 10^6 \text{ cal/h}$$

The heat transfer rate out of the condenser is 3.41 × 10^6 calories per hour.

The Second Law of Thermodynamics

Suppose you place an ice cube in the palm of your hand. The temperature of the ice is 0°C and your hand is 37°C. This temperature difference causes heat to flow from your palm to the ice. The internal energy transferred will begin to melt the ice and warm the resulting water. In accordance with the first law, the heat lost by your palm is gained by the ice and water.

Does it violate the first law for heat to flow in the opposite direction—from the ice cube to your palm—so the ice becomes colder and your palm warmer? Not if the internal energy lost by the ice equals that gained by your palm. But this process does violate the **second law of thermodynamics**. The second law can be stated in a number of equivalent ways. The simplest is a result of common observation:

> *The natural direction of heat flow is from a body (or reservoir) at a higher temperature to a body (or reservoir) at a lower temperature.*

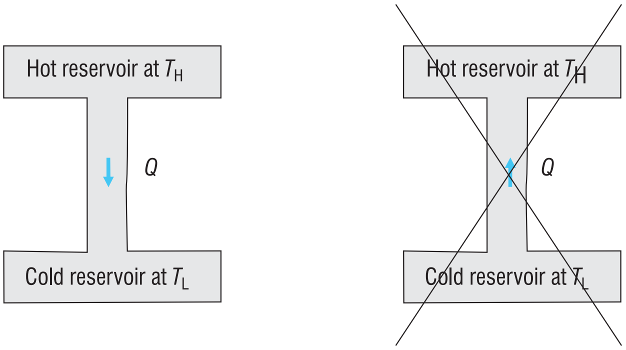
Heat can be made to flow the other way, as in a heat pump, but only by doing work and adding energy to the system. In the absence of this work, heat flows in one direction, from hot to cold. When you place a potato in a hot oven, heat flows from the oven to the potato, not from the potato to the oven. The potato gets hot and the oven gets slightly cooler. You will never see the potato get cold and the oven get hotter.

The second law of thermodynamics also applies to engines. In a heat engine, thermal energy in a working fluid is converted into mechanical work of a piston or wheel. Remember, the thermal energy of the working fluid is the sum of the kinetic energies of the randomly moving atoms and molecules in the fluid. To convert thermal energy into a usable form, the random motion of atoms and molecules must be converted into ordered motion of a piston or a wheel. It is impossible to convert 100% of the random motion. After a fluid does work on a moving piston or wheel, there will always be leftover thermal energy in the atoms and molecules of the working fluid. The leftover energy is transferred out of the engine, as heat, to a low-temperature reservoir.

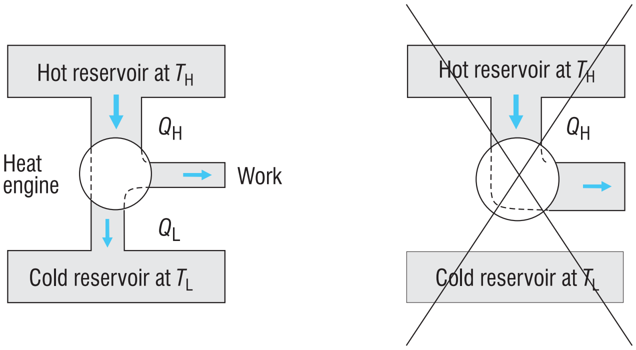
The second law of thermodynamics applied to heat engines can be stated as follows:

> *When work is done by an engine operating in a cycle, only some of the heat taken from a reservoir can be converted into work. The rest is rejected as heat at a lower temperature.*

Figure 5.37 illustrates the two statements of the second law.



Heat flows naturally from a high-temperature body to a cold-temperature body.



A heat engine can convert only some of the heat taken from a reservoir.

Figure 5.37
Two statements of the second law of thermodynamics

The second law of thermodynamics says that a heat engine cannot be 100% efficient in turning heat into work. Even an ideal engine with no friction has an upper limit to its efficiency. This upper limit was first described by the French engineer Sadi Carnot in 1824. The maximum efficiency of a heat engine is called the **Carnot efficiency**; it depends on only the *absolute temperatures* of the hot and cold reservoirs, T_H and T_L.

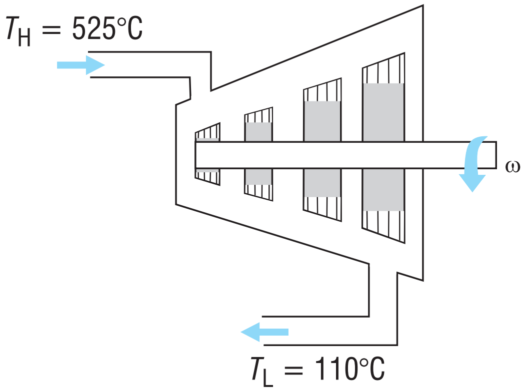
$$\text{Carnot efficiency} = 1 - \frac{T_L}{T_H}$$

The absolute temperature scale is also called the **Kelvin scale**. The zero point of the Celsius scale is the freezing point of water. The zero point of the Kelvin scale is the lower limit of the temperature of any substance, where the thermal energy of the substance is zero. It is impossible to lower the temperature below this point, and it is therefore called **absolute zero**. The interval on this scale is the **kelvin** (K). The degree symbol is not used with the Kelvin scale. For example, the freezing point of water (0°C) is 273 K. The boiling point of water (100°C) is 373 K. The conversion between Celsius and Kelvin temperatures is:

$$T_{\text{Kelvin}} = T_{\text{Celsius}} + 273$$

Example 5.18 Carnot Efficiency of a Turbine

High-pressure steam enters a turbine at a temperature of 525°C. The steam expands in the turbine and pushes on the blades of the turbine shaft, causing the shaft to rotate and do work. The steam exits the turbine at a lower pressure and a temperature of 110°C. What is the maximum efficiency of the turbine?



Solution: The steam transfers energy to the turbine at a high temperature of

$$\begin{aligned} T_H &= 525°\text{C} \\ &= 525 + 273 = 798\ \text{K} \end{aligned}$$

The steam exits the turbine at a low temperature of

$$\begin{aligned} T_L &= 110°\text{C} \\ &= 110 + 273 = 383\ \text{K} \end{aligned}$$

The Carnot efficiency of the turbine operating between these two absolute temperatures is

$$\begin{aligned} \text{Carnot efficiency} &= 1 - \frac{383\ \text{K}}{798\ \text{K}} \\ &= 0.52 \quad \text{or} \quad 52\% \end{aligned}$$

The maximum efficiency of the turbine is 52%.

Energy Dissipation

The Carnot efficiency, like that calculated for the turbine in Example 5.17, is for an "ideal" process. An actual turbine will have a lower efficiency, probably less than 40%. This is because some of the steam's energy will go into overcoming friction in the turbine's bearings, turbulence in the steam flow, and heat transfer to the air surrounding the turbine. These are sometimes called energy "losses." But the energy is not really lost. It still exists, but it is *dissipated*, or no longer available to do work on the turbine.

Energy dissipation occurs in all processes. When electrical energy flows through a light bulb, some of the energy produces visible light and some is dissipated as thermal energy that heats the bulb. When gasoline is burned in a car engine, some of the energy produces motion and operates equipment and some of the energy is dissipated as thermal energy that heats the Earth's atmosphere. Energy is not "used up" in mechanical, fluid, electrical, or thermal systems. But energy is converted from usable forms to unusable forms. Energy dissipation means there may never be a shortage of energy on the Earth, but someday there may be a shortage of energy in usable forms.

Summary

- A system's internal energy can be changed by transferring heat to (or from) the system and by doing work on (or by) the system.
- The first law of thermodynamics is a statement that energy is conserved in a system. A system's change in internal energy is the net heat input minus the work done. Heat transferred to a system is positive. Work done by a system is positive.
- An adiabatic process is one in which there is no heat transfer.
- A heat engine is a device that converts thermal energy into work.
- A refrigerator reverses the cycle of a heat engine. It converts work into thermal energy and moves heat away from a cold reservoir to a hot reservoir.
- The second law of thermodynamics limits the number of possible processes. Without outside work, heat flows in only one direction—from a hot reservoir to a cold reservoir. Only some of the heat taken from a reservoir to operate an engine can be converted into work—the rest is rejected as waste heat.
- The Carnot efficiency is the maximum possible efficiency of a heat engine. Carnot efficiency $= 1 - \frac{T_L}{T_H}$, where T_L and T_H are absolute temperatures, measured in the Kelvin scale. ($T_{Kelvin} = T_{Celsius} + 273$)

Exercises

1. The sum of the kinetic and potential energies of all the molecules that make up a system is called the system's _______________.

2. (a) Describe two ways of increasing the internal energy of a system.

   (b) Describe two ways of decreasing the internal energy of a system.

3. By convention, when using the first law of thermodynamics to solve problems,

   (a) if heat enters a system, it is a _______________ (positive or negative) quantity. In this case the internal energy of the system _______________ (increases or decreases).

   (b) if work is done by the system, it is a _______________ (positive or negative) quantity. In this case the internal energy of the system _______________ (increases or decreases).

4. Suppose you compress the air in a bicycle air pump adiabatically. Which of the following is true?

   (a) The temperature of the air is constant.

   (b) The pressure of the air is constant.

   (c) No heat enters or leaves the air.

   (d) No work is done on or by the air.

5. Describe two ways you can compress the air in a bicycle air pump adiabatically.

6. A heat engine operates by taking in heat at one temperature, converting some of it into work, and exhausting the rest at _________________ (a higher, a lower, or the same) temperature. The amount of heat exhausted is _______________ (greater than, less than, or the same as) the amount of heat taken in.

7. A refrigerator operates by doing work on a fluid that absorbs heat at one temperature and exhausting heat at _______________ (a higher, a lower, or the same) temperature. The amount of heat exhausted is _______________ (greater than, less than, or the same as) the amount of heat taken in.

8. Match each component of a refrigerator with its function.

   Components: compressor, condenser, expansion valve, evaporator

   (a) decreases the pressure of the working fluid

   (b) changes the phase of the working fluid from gas to liquid

   (c) does work on the working fluid to increase its pressure and temperature

   (d) changes the phase of the working fluid from liquid to gas

9. The ______________ (first or second) law of thermodynamics is a statement of the law of conservation of energy.

10. The ______________ (first or second) law of thermodynamics says that not all the heat taken into an engine can be converted into work.

11. According to a magazine article, the temperature of the sun's core is approximately 1.5 million degrees. Does it matter whether this temperature is in degrees Kelvin or degrees Celsius? Explain.

12. Which of the following is possible?

    (a) The temperature of a superconductor is –2 K.

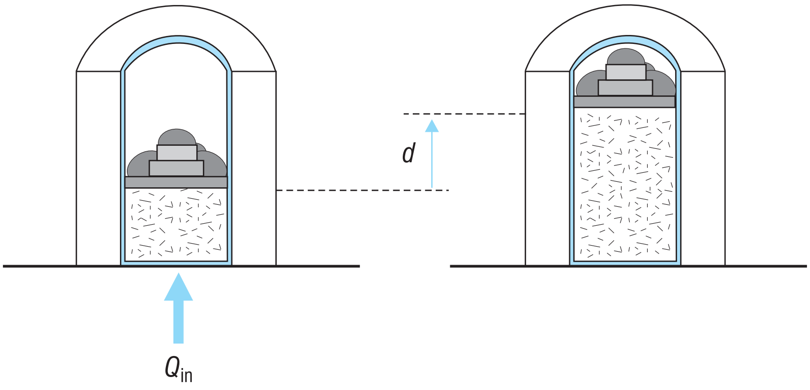
    (b) The efficiency of an ideal, friction-free engine is greater than the Carnot efficiency.

    (c) An engine that has attained the Carnot efficiency rejects no heat to a cold-temperature reservoir.

    (d) All of the above.

    (e) None of the above.

13. A cylinder contains a gas and a piston loaded with weights to maintain a constant pressure in the gas. The total weight of the piston and weights is 23.4 N. The side of the cylinder is insulated, but its bottom is not. When the cylinder is placed on a warm surface, heat flows into the gas and the gas expands. The piston rises a distance of 11.4 cm and then stops.



    (a) How much work is done by the gas in the cylinder during the expansion?

    (b) If the internal energy of the gas increases by 9.50 J, how much heat is transferred to the gas?

14. A thermos bottle contains cold coffee. Suppose you shake the bottle vigorously. Does the internal energy of the coffee increase, decrease, or stay the same? Explain your answer, using the first law of thermodynamics.

15. The cylinders of a car's engine are 85 mm in diameter. The pistons travel a length of 105 mm during each stroke. The average pressure of the fuel-air mixture in the cylinder during the compression stroke is 8.5×10^5 Pa.

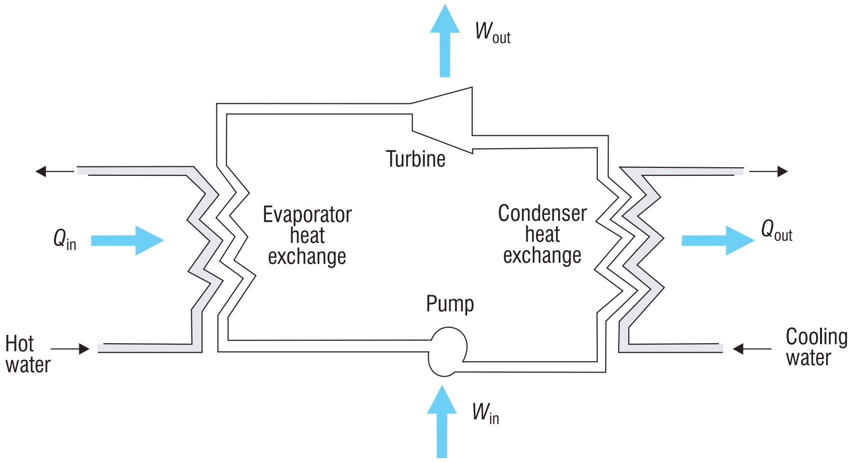
    (a) What is the work done on the fuel-air mixture during the compression stroke of one piston? (The volume of a cylinder is $\pi r^2 h$, where r is the radius and h is the height.)

    (b) The internal energy of the fuel-air mixture before the compression is 1440 J. What is the internal energy after the compression?

16. A 0.55-g hailstone falling at a terminal speed of 9.2 m/s strikes a concrete sidewalk. By how much does the internal energy of the hailstone change as it comes to a stop?

17. The Carnot efficiency of a heat engine is 65%. If heat is exhausted from the engine at a temperature of 113°C, at what temperature is heat absorbed by the engine?

18. A village in Iceland uses hot water from a geothermal well as a heat source for an electrical generation system. The system operates on a cycle and uses a working fluid that has a low boiling point, similar to the fluid used in a refrigeration system.



In the evaporator heat exchanger, 6.31×10^5 Btu per hour are absorbed by the working fluid from the hot water. In the condenser heat exchanger, 3.99×10^5 Btu per hour are removed from the working fluid. The pump does work at a rate of 3.16×10^5 Btu per hour.

(a) At what rate does the turbine in this system do work?

(b) The turbine drives an electrical generator. The efficiency of electrical energy generation is 85%. What is the electrical output, in kilowatts? (1 Btu = 1054 J and 1 J/s = 1 watt.)