CHAPTER 7

Thermal energy transfer and changes of state are the basis of many technologies.

Learning Expectations

By the end of this chapter, you will:

Relating Science to Technology, Society, and the Environment

- analyze thermal energy transfers and transformations in solar panels and a power station
- assess technologies related to thermal and geothermal energy

Developing Skills of Investigation and Communication

- use the law of conservation of energy to solve problems involving thermal energy
- solve problems involving power, energy, and time
- compare and contrast the input energy, useful output energy, and percent efficiency of selected energy generation methods
- conduct an inquiry to determine the specific heat capacity of a single substance and a mixture
- solve problems involving changes in temperature and changes of state
- draw and analyze heating and cooling curves

Understanding Basic Concepts

- explain *thermal energy*, *heat*, *specific heat capacity*, and *specific latent heat*
- relate efficiency and thermal energy transfer
- use the kinetic molecular theory to explain the energy transfer that occurs during changes of state
- distinguish between conduction, convection, and radiation

Thermal energy moves from warmer to cooler areas. Getting heat into a structure and not letting it leak out again is a technical challenge for engineers, architects, and builders. Another challenge is to find ways to harness thermal energy that are efficient and sustainable.

Every two years, university teams from around the world gather in Washington, D.C., to compete in a Solar Decathlon, a competition to design and build the most attractive, effective, and energy-efficient solar-powered house. In 2009, Team North — students and teachers from the University of Waterloo, Ryerson University, and Simon Fraser University — created North House, a solar powered home specially designed to meet the challenges and demands of northern climates (Figure 7.1). Team North's design came in fourth in the competition.

North House combines passive and active solar design to produce more energy than it consumes. Energy from the Sun streams through the south-facing windows, warming the walls, floors, and furniture. Well-designed window shades and good insulation in the walls keep the heat in at night. Solar panels on the roof provide energy for space heating and cooling, hot water, home entertainment, and appliances.

Figure 7.1 North House, a solar-powered house specially designed for northern climates

7.1 Temperature and Heat

Section Summary

- Thermal energy is the total kinetic and potential energy of the particles within an object.
- Heat is the energy transferred from a warmer object to a cooler object.
- Thermal energy can be transferred by conduction, convection, and/or radiation.
- The temperature of a substance is the average kinetic energy of its particles.
- The specific heat capacity of a substance is the amount of energy required to raise the temperature of 1 kg of the substance by 1 K, or 1°C.
- The principle of heat exchange is an example of the law of conservation of energy.

Early scientists thought that heat was an invisible fluid, which they called *caloric*. They thought this fluid flowed from hot materials to cold materials, producing a temperature change. Then, in 1738, mathematician Daniel Bernoulli (1700–1782) proposed that gases consist of great numbers of particles moving in all directions, and that what we experience as heat is simply the kinetic energy of their motion. This theory was not immediately accepted.

In 1845, English physicist James Joule (1818–1889) performed an experiment that showed that work can produce a temperature change. He used a device similar to that shown in Figure 7.2. Gravity does work on the masses as they fall. The masses pull the strings, causing the beaters to turn and do work on the water. The temperature of the water gradually rises. Careful measurement of the work done on the masses and the temperature change in the water showed that it takes 4.184 J of energy to raise the temperature of 1.00 g of water from 14.5°C to 15.5°C. This experiment showed that heat, like work, is energy transferred between substances or objects.

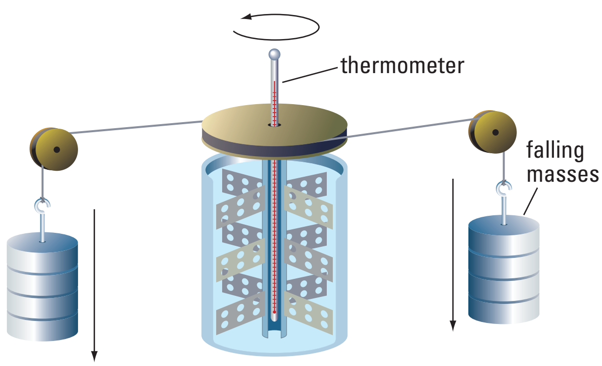


Figure 7.2 Joule's experiment showed that both heat and work are energy transferred between objects.

The Kinetic Molecular Theory of Matter

The **kinetic molecular theory of matter** states that matter is made up of particles (molecules, atoms, or ions) that are in constant random motion. These particles are continually vibrating and rotating. Vibrations are motions within or between particles that repeatedly increase and decrease the distance between particles. A rotating particle spins around an axis.

Thermal Energy

The particles that make up matter have kinetic energy because of their motion. As particles vibrate, their energy constantly alternates between kinetic energy and elastic potential energy. Particles also have potential energy due to the forces of attraction or chemical bonds between them.

Thermal energy is the total kinetic and potential energy of the particles within an object. Thermal energy is internal energy — the energy associated with the movement and interactions of particles (Figure 7.3). An object has thermal energy in addition to any potential energy or kinetic energy it may have as a whole due to the motion of the object to which the particle belongs.

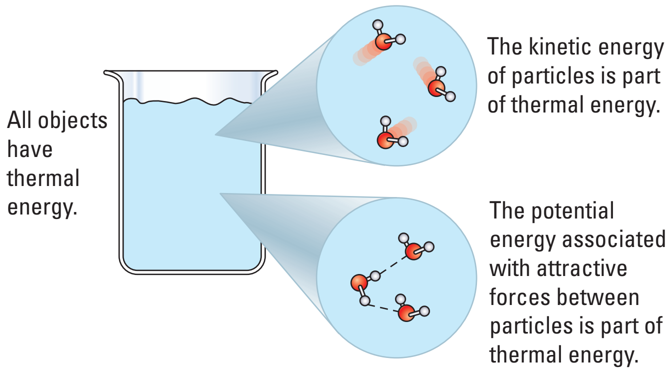


Figure 7.3 The thermal energy of an object is the kinetic and potential energy of its particles.

Temperature

As particles move, they collide, and when they do, they transfer kinetic energy back and forth among themselves. The greater the speed of a particle, the greater its kinetic energy. Faster particles transfer kinetic energy to slower particles, increasing their speed. In this way, energy can be transferred from one part of a substance to another or from one object to another.

The **temperature** of a substance is the average kinetic energy of its particles. The greater the average kinetic energy of all of an object's particles, the higher the object's temperature.

At higher temperatures, the particles in solids will vibrate more vigorously; in liquids and gases, they will move about, rotate, and vibrate more quickly.

The Kelvin Scale

Absolute zero is the lowest temperature that is theoretically possible. At absolute zero, molecular motion and energy would be minimal, though there would still be at least some small quantity of energy.

Absolute zero cannot be reached on Earth or in a laboratory, but scientists have developed a technique called *laser cooling* that can cool atoms to temperatures within a billionth of a degree of absolute zero.

The average temperature of the universe is not much higher than absolute zero.

PHYSICS INSIGHT

Except when a high level of precision is needed, it is adequate to use $0°C = 273\ K$.

$$T(\text{K}) \underset{-273}{\overset{+273}{\rightleftarrows}} T(°\text{C})$$

The unit of temperature measurement in the SI system is the **kelvin (K),** after British physicist Lord Kelvin (1824–1907). Lord Kelvin's work helped connect temperature to the kinetic molecular theory of matter. Absolute zero in the Kelvin scale is 0 K, or –273.15°C.

The freezing point of water is 273.15 K, or 0°C. The boiling point of water is 373.15 K, or 100°C. A temperature change of 1 K is the same as a temperature change of 1°C.

PHYSICS•SOURCE

Explore More

How did scientists determine the value of absolute zero on the Celsius scale?

Heat

Heat is the energy transferred from a warmer object to a cooler object (Figure 7.4). Unlike work, which requires motion that changes the position of the object's centre of mass, heating involves energy transfer on the microscopic level.

The particles in the hot chocolate shown in Figure 7.5 are vibrating rapidly and moving about; there is lots of thermal energy. As particles of the hot liquid collide with particles of the cup, kinetic energy is transferred. The particles of the liquid now move less quickly, and the liquid gets a bit cooler — it has less thermal energy. The particles of the cup move more quickly, however, and the cup gets hotter — it has gained thermal energy.

When you put cool fingers around a warm cup, some of the energy in the cup is transferred to the particles of your skin, and your hand grows warmer. The thermal energy of the cup becomes thermal energy in your fingers. Eventually, through the transfer of thermal energy, the hot chocolate, cup, and hands all reach the same temperature.

If one object is hotter than another and they are in contact, thermal energy passes from the one with the higher temperature (higher average kinetic energy) to the one with the lower temperature (lower average kinetic energy). If objects of the same temperature (same average kinetic energy) are in contact, there is no transfer of thermal energy.

The kinetic molecular theory of matter helps to explain why mechanical energy is often partially transformed into thermal energy. When two objects that are at the same temperature are in contact but not moving, there is no transfer of thermal energy. But when the contacting surfaces are rubbed against one another, friction converts some of the mechanical energy to thermal energy, causing a rise in temperature.

When you rub your hands together quickly, work is done. *Some* of the energy transferred is transferred as thermal energy, and your hands get warmer. Any interaction that involves moving objects or materials in contact with each other converts some mechanical energy to thermal energy, and causes some rise in temperature. This is why no mechanical process can be perfectly efficient.

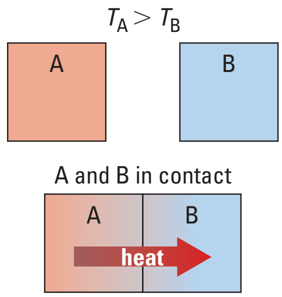


Figure 7.4 Heat is energy transferred from a higher-temperature object to a lower-temperature object.

Figure 7.5 An object feels warm or hot if its temperature is higher than that of your skin. The particles in a warm cup have more kinetic energy than the particles in cool hands, so thermal energy is transferred from the cup to the hands.

Concept Check

1. Describe the kinetic molecular theory of matter.
2. What is temperature?
3. Describe the relationship between thermal energy and heat.

Thermal Energy Transfers

Thermal energy can be transferred from one place to another by conduction, convection, and/or radiation. Often, transfer of thermal energy occurs through two or even all three processes simultaneously.

Conduction

A hot iron warms the wrinkles out of a shirt, and a cold tile floor chills your feet. **Conduction** is the transfer of thermal energy through direct contact between the particles of two substances, without the particles moving to a new location. The energetic particles of the warmer material collide with the less energetic particles of the cooler material. The slower particles gain energy and collide with other particles in the cooler object. It takes a while for all the particles in each of the two materials to have the same average kinetic energy. At this point, both objects are at the same temperature. The objects then stop exchanging energy. At that point, they have reached a state of **thermal equilibrium**.

Since the particles in solids are closer together, solids conduct thermal energy better than liquids, and liquids conduct thermal energy better than gases. Good conductors of electricity, such as metals, are often good conductors of thermal energy.

Figure 7.6 When you boil water, the water at the bottom of the pot is heated first, as thermal energy is transferred to the water from the pot by conduction. Convection in the water transfers energy through the movement of particles from one location to another.

Convection

Convection is the transfer of thermal energy through the bulk movement of particles from one location to another. Convection occurs in fluids (liquids and gases), where the particles have freedom of movement and are not locked in place as they are in a solid.

As shown in Figure 7.6, convection is a natural stirring of a fluid: hotter, less dense material flows up while cooler, denser material flows down. Eventually, all the material is heated to a uniform temperature. In liquids and gases, convection is usually the most efficient way to transfer thermal energy.

Radiation

Radiation is the transfer of energy as electromagnetic waves or fast-moving particles. The energy transferred in these waves or particles is called **radiant energy.** The most common types of radiant energy are visible light and other sorts of electromagnetic radiation, such as infrared and ultraviolet radiation.

Figure 7.7 Radiant energy emitted by the burning coals in the barbecue heats the grill and the bottom of the pan. This energy is transferred to the rest of the pan by conduction. Thermal energy also passes from the grill to the pan to the food in the pan by conduction.

When you hold your hands near a wood stove, a light bulb, or an electric baseboard heater, you feel warmth even though there is no contact — radiation carries energy through empty space. When radiant energy reaches an object, it is transferred to the object's particles as kinetic energy, and the temperature of the material rises (Figure 7.7).

All objects absorb energy from radiation and emit energy in the form of radiation. When objects are at the same temperature, the amount of energy absorbed equals the amount given off, and no temperature changes occur.

Thermal energy always moves from areas of higher to lower temperature unless an external force does work at the same time (for example, in a refrigerator, thermal energy is removed from the colder part).

Heating

Many of the devices we use to heat buildings and food rely on a combination of conduction, radiation, and convection to transfer thermal energy:

- *Open fireplace:* Some energy from the chemical reaction of the burning wood (combustion) radiates directly into the room or to the surrounding brick or stone. Thermal energy is conducted through the brick or stone and then radiates into the room. Much of the energy from the fire heats air, which goes up the chimney by convection.
- *Gas or oil furnace:* Energy from combustion is transferred to a metal heat exchanger by radiation. The heat exchanger uses conduction to heat air. A fan forces the hot air to circulate throughout the building. In modern high-efficiency furnaces, much of the thermal energy in the combustion gases is captured instead of going up the chimney.
- *Convection oven:* The electric heating element gets hot when moving electrons transfer electrical potential energy to particles in the element. The particles' thermal energy is transformed into infrared and visible radiation, and you see the element glow. The radiation warms the walls of the oven and the food. The hot air in the oven warms the food by conduction. A special fan forces circulation of the hot air (convection) to speed up the transfer of thermal energy.
- *Microwave oven:* A magnetron tube is used to produce microwave radiation, which is absorbed by the bonds in the water molecules in the food to be heated or thawed. This energy is transformed into kinetic energy of the water molecules, increasing their internal vibrational and rotational motion. Then, through conduction, this energy is shared by all of the molecules in the food and the oven.

Insulation

Nothing can stop the transfer of thermal energy from warmer to cooler areas, but the transfer can be slowed down. Materials or methods used to reduce the rate of thermal energy transfer are called **thermal insulation**. The three basic methods of heating give rise to three basic concepts for insulation.

- Seal it well — prevent convection.
- Reflect it back — prevent radiation.
- Put it in a blanket — prevent conduction.

A vacuum flask (Figure 7.8) keeps drinks hot or cold by preventing thermal energy transfer in four ways:

- A vacuum contains no matter, so it cannot transfer thermal energy by conduction or convection.
- Radiation can travel through a vacuum. The outer layer of the flask is reflective, preventing transmission of infrared radiation.
- When the stopper is screwed on tightly, there is still convection going on within the liquid in the flask, but it is contained.
- An air space between the outer layer and the casing isolates the contents from the environment.

These features significantly reduce transfer of thermal energy, and the contents of a vacuum flask will stay hot or cold for hours.

PHYSICS INSIGHT

Often a problem can be solved by working backward. To keep something warm, prevent it from transferring thermal energy.

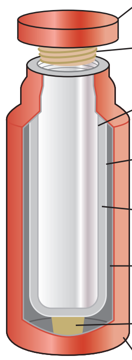


Figure 7.8 A vacuum flask prevents transfer of thermal energy by conduction, convection, and radiation.

Figure 7.9 Glass fibre insulation is used for energy conservation in buildings.

To reduce the transfer of warm air from the inside to the outside of a building, you can caulk gaps to stop drafts and, in new construction, install a vapour barrier in exterior walls. A layer of fibre glass batting in an attic separates a warm ceiling from a cold roof, preventing conduction (Figure 7.9). An energy-efficient film on the windows stops these surfaces from emitting infrared radiation.

PHYSICS•SOURCE

Explore More

How does spacesuit technology help astronauts survive the temperature extremes of outer space?

Concept Check

1. Which type or types of thermal energy transfer occur in each of the following situations?
   (a) You warm your hands on a cup of hot chocolate.
   (b) You warm a cup of soup in a microwave oven.
   (c) You bake a pizza on a metal tray in the oven.
2. Explain why a vacuum does not conduct thermal energy.
3. Explain how a space blanket (reflective sheet of polyester) can help to keep you warm.

Heat Capacity

Heating a plate of food in a microwave oven is as easy as pushing a button — but your meal will still be too cold, or too hot, unless you add the right amount of energy. The amount of thermal energy required depends on three factors:

- *Mass:* Are you heating a small bowl of beans or a large bowl of beans? It takes more energy to heat a greater mass of a given substance (Figure 7.10).
- *Temperature change:* Are you just taking the chill off a piece of pizza, or do you want to make it sizzling hot? It takes more energy to achieve a greater temperature change.
- *Type of material:* Are you heating a cup of water or a cup of milk? Different materials require different amounts of thermal energy to reach the same temperature.

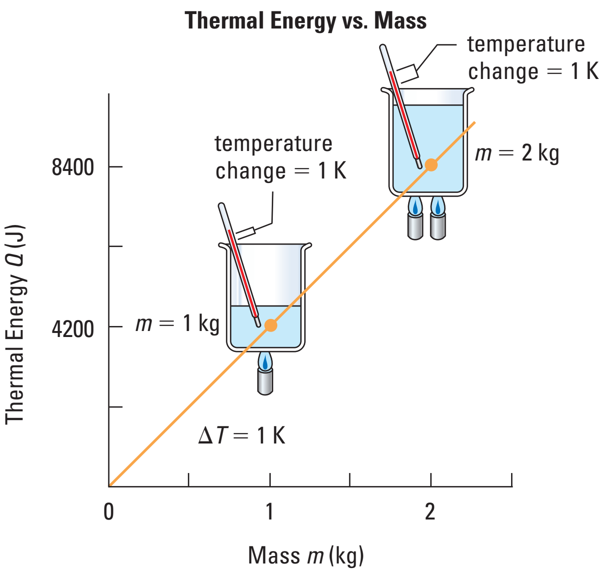


Figure 7.10 It takes twice as much thermal energy to warm double the mass of a substance through the same temperature change.

Heat capacity is the amount of thermal energy needed to change the temperature of an object or system by 1 K, or 1°C. Heat capacity is measured in joules per kelvin. The heat capacity of 250 mL of water is about 1000 J/K. It takes about 1000 J of thermal energy to raise the temperature of 250 mL of water by 1 K.

Heat capacity is directly proportional to mass: the heat capacity of 1000 mL, or 1 L, of water is about 4000 J/K, and the heat capacity of a 5-L pot of water is about 20 000 J/K.

Specific Heat Capacity

If you walk in bare feet on a hot day, you will notice that some surfaces are much hotter than others, even though they receive the same amount of radiant energy. This is because the surfaces are made from materials with different specific heat capacities.

The **specific heat capacity (*c*)** of a substance is the amount of energy required to raise the temperature of 1 kg of the substance by 1 K, or 1°C. It takes much less energy to raise the temperature of 1 kg of sand by 1 K than it does to raise the temperature of 1 kg of wet mud by 1 K, so the sand gets hotter than the mud when exposed to the same amount of sunlight.

As shown in Figure 7.11, two objects made of exactly the same material will have the same specific heat capacity.

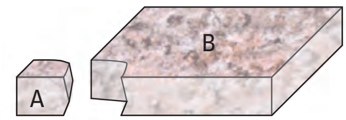


Figure 7.11 The heat capacity of a large slab of granite is greater than that of a small chip of granite, but the specific heat capacities of the slab and the chip are the same.

Specific heat capacity is measured in joules per kilogram per kelvin (J/(kg·K)). The specific heat capacity of liquid water is about 4190 J/(kg·K). This means that it takes 4190 J of energy to raise the temperature of 1.00 kg of water by 1.00 K. Specific heat capacities of some common materials are given in Table 7.1.

Specific heat capacity is a physical property of a material. It depends on the substance's chemical structure and on its state. In general, solids have lower specific heat capacities than liquids and gases. Specific heat capacities are determined by experiment and are known for many thousands of substances. Measuring the specific heat capacity of an unknown substance can help to identify it.

Table 7.1 Some Specific Heat Capacities

Substance	*c* (in J/(kg·K))
Plastic	167
Wood (pine)	250
Bone	440
Stainless steel	510
Glass (lab ware)	750
Sand (quartz)	830
Asphalt	920
Air, dry (sea level)	1005
Clay	1391
Vegetable oil	1670
Water (vapour)	2000
Ethylene glycol (antifreeze)	2360
Water (ice, 0°C)	2093
Wet mud	2512
Human body	3470
Milk	3930
Water (liquid)	4190

Concept Check

1. Define heat capacity and specific heat capacity.
2. Explain the unit of specific heat capacity.
3. Why is the specific heat capacity of the human body close to, but somewhat less than, that of water?

Quantity of Thermal Energy

In physics, Q represents the **quantity of thermal energy**, in joules, transferred to an object or system resulting in a change in temperature:

$$Q = mc\Delta T$$

where m is the mass of the object, in kg, c is the specific heat capacity of the substance that makes up the object, in J/(kg·K), and ΔT is the temperature change of the object, in K.

A positive value of Q indicates that a substance has absorbed thermal energy from its surroundings. A negative value of Q indicates that a substance has released thermal energy to its surroundings. The amount of thermal energy a substance absorbs equals the energy lost by its surroundings. The amount of thermal energy a substance releases equals the energy gained by its surroundings.

Example 7.1

A 515-g granite rock cools from 450°C to 100°C. The specific heat capacity of granite is 790 J/(kg·K). Calculate how much thermal energy is lost by the rock.

Given

$m = 515 \text{ g} = 0.515 \text{ kg}$
$T_\text{i} = 450°\text{C}$
$T_\text{f} = 100°\text{C}$
$c = 790 \text{ J/(kg·K)}$

Required

quantity of thermal energy (Q)

Analysis and Solution

Calculate the change in temperature. Since a temperature change of 1°C is the same as a temperature change of 1 K, there is no need to convert the temperatures to Kelvin before finding the temperature change. Next, substitute into $Q = mc\Delta T$.

$$\begin{aligned}\Delta T &= T_\text{f} - T_\text{i} \\ &= 100°\text{C} - 450°\text{C} \\ &= -350°\text{C} \\ &= -350 \text{ K}\end{aligned}$$

$$\begin{aligned}Q &= mc\Delta T \\ &= (0.515 \cancel{\text{kg}})\left(790 \frac{\text{J}}{\cancel{\text{kg}}\cdot\cancel{\text{K}}}\right)(-350 \cancel{\text{K}}) \\ &= -1.4240 \times 10^5 \text{ J} \\ &= -142 \text{ kJ}\end{aligned}$$

Paraphrase

The hot rock loses about 142 kJ of thermal energy.

Practice Problems

1. A 215-g mass of water at 4.00°C is allowed to warm to 22.1°C. Determine the amount of thermal energy absorbed by the water.
2. How much thermal energy must be added to a 97.3-g mass of water at 23.2°C to raise its temperature to 100.0°C?
3. When 574 J of energy is added to 20.0 g of aluminum, the temperature of the aluminum rises 32.0°C. Find the specific heat capacity of aluminum.

Answers

1. 16.3 kJ
2. 31.3 kJ
3. 897 J/(kg·K)

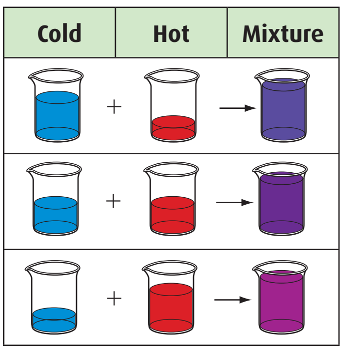
The Principle of Heat Exchange

You test the temperature of the bath water: "Ouch, that's too hot!" You then mix in cold water until the temperature is just right. Or you may add hot water to warm water to make it even warmer. The law of conservation of energy says that the thermal energy gained by the cold water is equal to the thermal energy lost by the hot water. This can be restated as the **principle of heat exchange**:

> When two substances at different temperatures are mixed, the amount of thermal energy lost by the hotter substance in cooling is equal to the amount of thermal energy gained by the colder substance in warming.

For example, if you mix together various amounts of hot and cold water, the final temperature will depend on the proportions of hot and cold water you use, as shown in Table 7.2.

Table 7.2 Mixing Cold and Hot Water



If you mix together two substances that are at initial temperatures T_{i_1} and T_{i_2}, you can use the principle of heat exchange to predict the final temperature, T_f:

$$Q_1 + Q_2 = 0$$
$$m_1c_1(\Delta T)_1 + m_2c_2(\Delta T)_2 = 0$$
$$m_1c_1(T_f - T_{i_1}) + m_2c_2(T_f - T_{i_2}) = 0$$
$$m_1c_1(T_f - T_{i_1}) = -m_2c_2(T_f - T_{i_2})$$

The thermal energy gained by the cooler substance equals the thermal energy lost by the warmer substance.

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Suggested Activity

- C7 Quick Lab Overview on page 218

Example 7.2

An insulated cup containing 255 g of water at 21.6°C is emptied into another insulated cup containing 407 g of water at 63.8°C. Determine the final temperature of the mixture, assuming that no thermal energy is lost.

Given

$m_1 = 255 \text{ g} = 0.255 \text{ kg}$
$T_{i_1} = 21.6°\text{C}$
$m_2 = 407 \text{ g} = 0.407 \text{ kg}$
$T_{i_2} = 63.8°\text{C}$
$c_1 = c_2 = 4190 \text{ J/(kg·K)}$

Required

final temperature of mixture (T_f)

Analysis and Solution

Substitute into the heat exchange formula:

$$m_1c_1(T_f - T_{i_1}) = -m_2c_2(T_f - T_{i_2})$$

$$(0.255 \text{ kg})\left(4190 \frac{\text{J}}{\text{kg·K}}\right)(T_f - 21.6°\text{C}) = -(0.407 \text{ kg})\left(4190 \frac{\text{J}}{\text{kg·K}}\right)(T_f - 63.8°\text{C})$$

Divide out the common factors. Then divide by 0.255 and simplify.

$$(0.255 \cancel{\text{kg}})\left(\cancel{4190 \frac{\text{J}}{\text{kg·K}}}\right)(T_f - 21.6°\text{C}) = -(0.407 \cancel{\text{kg}})\left(\cancel{4190 \frac{\text{J}}{\text{kg·K}}}\right)(T_f - 63.8°\text{C})$$

$$0.255(T_f - 21.6°\text{C}) = -0.407(T_f - 63.8°\text{C})$$
$$(T_f - 21.6°\text{C}) = -\frac{0.407}{0.255}(T_f - 63.8°\text{C})$$
$$= -1.5961(T_f - 63.8°\text{C})$$

Expand the right side and collect like terms. Solve for T_f.

$$T_f - 21.6°\text{C} = -1.5961T_f + 101.83°\text{C}$$
$$2.5961T_f = 123.43°\text{C}$$
$$T_f = \frac{123.43°\text{C}}{2.5961}$$
$$= 47.54°\text{C}$$

Paraphrase

The final temperature of the water is about 47.5°C.

Practice Problems

1. The specific heat capacity of milk is 3930 J/(kg·K). Find the final temperature if 312 g of milk at 21.8°C is mixed with 189 g of milk at 95.2°C.
2. Turpentine has a specific heat capacity of 1700 J/(kg·K). A jar containing 94.8 g of turpentine at 15.1°C is poured into a jar containing 152 g of turpentine at 27.2°C. If no thermal energy is lost, what is the final temperature of the mixture?
3. The specific heat capacity of porcelain is 107 J/(kg·K). A 164-g porcelain cup at 21.2°C is filled with 197 g of water at 95.3°C. Assuming that no thermal energy is lost, determine the final temperature of the cup and water.

Answers

1. 49.5°C
2. 22.6°C
3. 93.8°C

Concept Check

1. Use the law of conservation of energy to explain the principle of heat exchange.
2. When two materials are in contact, why is thermal energy transferred from the warmer material to the cooler material?
3. Describe the various changes that occur in the kinetic energy of the water molecules when cold water is mixed with hot water.

PHYSICS•SOURCE

Suggested Activity

- C8 Inquiry Activity Overview on page 218

Measuring Specific Heat Capacity

A **calorimeter** is a device used to measure the transfer of thermal energy. It has a container in which to mix materials, insulation around the container, and a lid with holes for a stirring rod and a thermometer. A calorimeter may be as simple as two nested foam cups with a tight lid. The laboratory calorimeter shown in Figure 7.12(b) has an air gap around the central beaker. You can determine the specific heat capacity of a substance using a calorimeter and the principle of heat exchange.

Figure 7.12 shows how to measure the specific heat capacity of a block of metal:

1. Start with a calorimeter containing a known amount of cold liquid.
2. Heat the metal block of known mass (Figure 7.12(a)) to a known temperature and transfer it to the calorimeter (Figure 7.12(b)).
3. Measure how much the temperature of the liquid rises.
4. From this, calculate how much thermal energy was gained by the liquid and lost by the metal.
5. Calculate the specific heat capacity of the metal.

Specific heat capacities for a selection of metals are given in Table 7.3.

Table 7.3 Specific Heat Capacities of Some Metals

Metal	Specific Heat Capacity (J/(kg·K))
Gold	130
Silver	230
Copper	385
Iron	452
Titanium	544
Aluminum	896
Magnesium	1013
Beryllium	1885

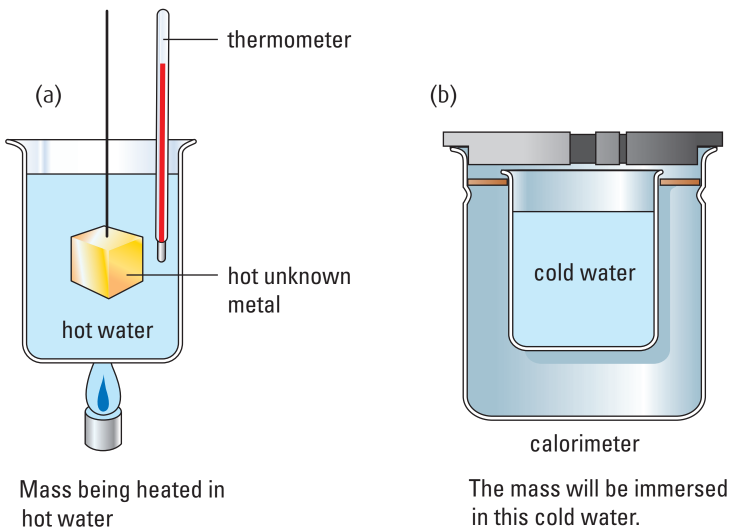

Figure 7.12 Using the principle of heat exchange to find the specific heat capacity of a metal

Example 7.3

A 64.9-g metal block is heated to 99.9°C in boiling water. It is carefully transferred to a calorimeter containing 131 g of isopropyl alcohol (specific heat capacity 2370 J/(kg·K)) at 11.0°C. The final temperature is 25.0°C. Find the specific heat capacity of the metal. Use Table 7.3 to identify which metal this might be.

Given

$m_1 = 131 \text{ g} = 0.131 \text{ kg}$ $m_2 = 64.9 \text{ g} = 0.0649 \text{ kg}$

$T_{i_1} = 11.0°\text{C}$ $T_{i_2} = 99.9°\text{C}$

$c_1 = 2370 \text{ J/(kg·K)}$ $T_f = 25.0°\text{C}$

Required

specific heat capacity of the metal (c_2)

Analysis and Solution

Use $Q = mc\Delta T$ to calculate Q_1, the quantity of thermal energy gained by alcohol.

$$\begin{aligned} Q_1 &= m_1c_1(T_f - T_{i_1}) \\ &= (0.131 \text{ kg})\left(2370 \frac{\text{J}}{\text{kg·K}}\right)(25.0°\text{C} - 11.0°\text{C}) \\ &= (0.131 \text{ kg})\left(2370 \frac{\text{J}}{\text{kg·K}}\right)(14.0°\text{C}) \\ &= (0.131 \cancel{\text{kg}})\left(2370 \frac{\text{J}}{\cancel{\text{kg·K}}}\right)(14.0 \cancel{\text{K}}) \\ &= 4346.58 \text{ J} \end{aligned}$$

This is the amount of thermal energy lost by the metal. Solve for c_2.

$$\begin{aligned} Q_2 &= m_2c_2(T_f - T_{i_2}) \\ -4346.58 \text{ J} &= (0.0649 \text{ kg})(c_2)(25.0°\text{C} - 99.9°\text{C}) \\ &= (0.0649 \text{ kg})(c_2)(-74.9°\text{C}) \\ &= (0.0649 \text{ kg})(c_2)(-74.9 \text{ K}) \\ c_2 &= \frac{-4346.58 \text{ J}}{(0.0649 \text{ kg})(-74.9 \text{ K})} \\ &= 894.17 \frac{\text{J}}{\text{kg·K}} \end{aligned}$$

Paraphrase

The specific heat capacity of the metal block is about 894 J/(kg·K). Checking Table 7.3, we might conclude that the block is made of aluminum, since our number falls closest to the number of aluminum.

Practice Problems

1. If 1.35 kg of crushed glass (specific heat capacity 500 J/(kg·K)) at 23.3°C are mixed with 2.15 kg of dry sand at 156°C, the final temperature of the mixture is 119°C. Find the specific heat capacity of this type of dry sand.
2. When 435 g of water at 95.2°C are mixed with 435 g of another liquid at 14.8°C, the final temperature of the mixture is 65.2°C. Determine the specific heat capacity of the second liquid.
3. A 2.65-kg piece of solid granite at 85.3°C is immersed in 2.65 kg of water at 15.6°C. The final temperature is 26.7°C. Determine the specific heat capacity of this type of granite.

Answers

1. 812 J/(kg·K)
2. 2.49 kJ/(kg·K)
3. 794 J/(kg·K)

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Take It Further

Meteorologists use the term *wind chill factor* to describe the combined effect of wind and cold temperatures. Canadian scientist Randall Osczevski proposed a new way to calculate wind chill factor that is more useful for humans. Investigate how the United States and Canada now calculate wind chill and write a short report.

Concept Check

1. Describe how a calorimeter prevents transfer of thermal energy to the surroundings.
2. Figure 7.12 shows how to measure the specific heat capacity of a metal block. How is the temperature change of the water affected by the mass of the block?
3. Describe how you could use a calorimeter to measure the heat capacity of a cold object.

C7 Quick Lab

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Mixing Water at Different Temperatures

Purpose

To investigate heat exchange when amounts of water at different temperatures are mixed

Activity Overview

In this activity, you will mix varying amounts of hot and cold water in a foam cup calorimeter and measure the initial and final temperatures. You will calculate the amounts of thermal energy gained by the cold water and lost by the hot water and investigate trends in these quantities.

Your teacher will give you a copy of the full activity.

Prelab Questions

Consider the questions below before beginning this activity.

1. Give an example from your daily experience of mixing hot and cold liquids.
2. Predict what determines the final temperature of a mixture of hot and cold liquids.

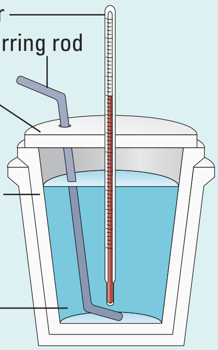

Figure 7.13 A simple foam cup calorimeter

DI Key Activity

C8 Inquiry Activity

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REQUIRED SKILLS

- Recording and organizing data
- Evaluating procedures

Investigating Specific Heat Capacity

Question

How different are the specific heat capacities of iron and copper?

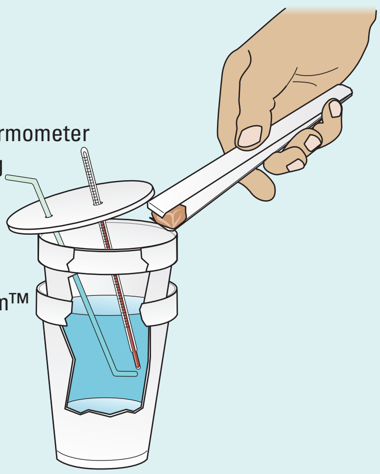

Figure 7.14 A piece of heated metal is placed in room-temperature water in a calorimeter.

Activity Overview

You will use a calorimeter to determine the specific heat capacities of iron and copper. By measuring several masses and temperatures and using the principle of heat exchange, you will be able to calculate the required specific heat capacities. The challenge of the activity is to make precise measurements and to carefully limit transfer of thermal energy to the surroundings.

Your teacher will give you a copy of the full activity.

Prelab Questions

Consider the questions below before beginning this activity.

1. What quantities do you need to know to find the specific heat capacity of a material?
2. Describe how you might measure each of the quantities you identified in question 1.

7.1 Check and Reflect

Key Concept Review

1. Describe how temperature is related to the kinetic molecular theory of matter.
2. How does heat differ from thermal energy?
3. Explain why heat is equivalent to work.
4. What factors determine how much thermal energy is needed to warm a cup of soup?
5. Give an example of the principle of heat exchange.
6. What is a calorimeter? Why is a calorimeter used in heat experiments?
7. Give an example of each of the three ways to transfer thermal energy.

Connect Your Understanding

8. Nitrogen, hydrogen, and helium in their liquid states are used as coolants in low-temperature experiments. Convert the following condensation temperatures into kelvin, to 4 significant digits.
(a) nitrogen: –195.79°C
(b) hydrogen: –252.87°C
(c) helium: –268.934°C

Question 8 Liquid nitrogen

9. The magnets of the Large Hadron Collider must be kept very cold (−271°C) to be strong enough to guide the proton and anti-proton beams. This is done by surrounding the magnets with a 1.9-K liquid helium bath.
(a) Which temperature is colder, −271°C or 1.9 K?
(b) In which direction does heat flow between the magnets and the bath? Explain.
10. Use an example to describe the relation between heat loss and less-than-perfect efficiency.
11. Describe how you might calibrate (accurately measure) the power output of a microwave oven or hot plate.
12. Describe how you could use a hot plate to measure the specific heat capacity of sunflower oil.
13. The specific heat capacity of pure water at 15.0°C is 4184 J/(kg·K). Convert this to kcal/(kg·K).
14. Find the quantity of thermal energy needed to warm a 7.5-kg block of concrete (c = 900 J/(kg·K)) from 5.0°C to 30°C.
15. A microwave oven delivers 800 W of output power. How much time does it take to warm 150 g of water from 15°C to 100°C?
16. The specific heat capacity of ethylene glycol is 2200 J/(kg·K). Determine the final temperature when 1.73 kg of ethylene glycol at 25.4°C are mixed with 2.47 kg of ethylene glycol at 89.2°C.
17. A 763-g lump of tar at 60.0°C is immersed in 1.41 kg of water at 13.0°C. After a while, both the water and tar have a temperature of 20.2°C. Determine the specific heat capacity of tar.
18. When 1.25 kg of a cold metal at a temperature of 263 K was immersed in 1.43 kg of water at a temperature of 365 K, the final temperature was 336 K. What is the specific heat capacity of the metal?
19. Use the kinetic theory of matter to explain why
(a) many solids expand as they get warm
(b) gas exerts pressure on its container

Reflection

20. What did you learn about heat that you didn't know before you started this section?
21. What did you find the most interesting about thermal energy transfers?

For more questions, go to PHYSICS•SOURCE

7.2 Changes of State

Section Summary

- Heating and cooling curves can be used to model transfers of thermal energy.
- A change of state, or phase transition, occurs when energy is transferred to or from a substance at its boiling or melting point.
- Latent heat is the energy that is needed for a phase change.
- Temperature remains constant during a phase change.
- Heat pumps do work to transfer energy from cooler areas to warmer areas.

Figure 7.15 Water keeps us cool in the summer's heat.

The people shown in Figure 7.15 are having fun and keeping cool at the same time. Water has a specific heat capacity about four times that of air, so it takes a lot longer to heat up. On a hot day, the water temperature will be lower than the air temperature — so going into the water feels good.

You feel even cooler when you get out of the water. To evaporate, molecules of liquid water need energy to break their bonds with other water molecules. They gain this energy by absorbing heat from your skin. As the molecules of water vapour move away from your body, they take this energy with them, cooling you off.

Changing state, especially from liquid to gas, takes a lot of energy. The large quantity of thermal energy absorbed or released when a substance changes state has practical uses in refrigerators, air conditioners, and other heat pumps, and in steam turbines.

Heating and Cooling Curves

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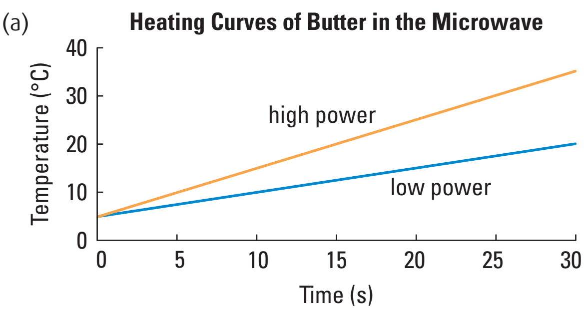
Suggested Activity

- C9 Inquiry Activity Overview on page 228

You are making toast and go for the butter, only to find there is no soft butter out on the counter, just hard butter in the refrigerator.

A quick electronic solution is to use a microwave oven. A microwave oven is a constant power device: it puts the same amount of energy into the butter each second. The temperature of the butter rises by the same amount each second, so the graphs of temperature against time are straight lines (Figure 7.16(a)). At high power, the temperature rises quickly and the graph is steep. At low power, the temperature rises slowly and the graph is less steep.



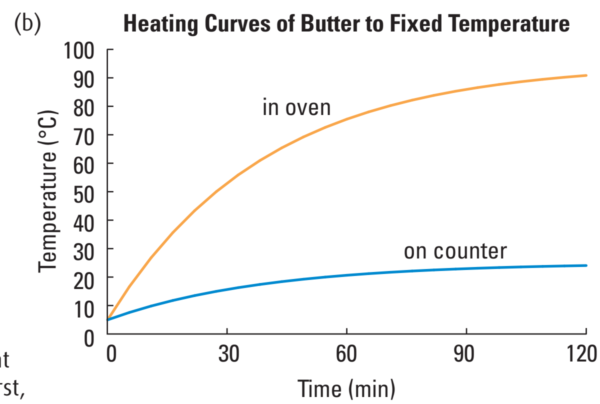


Figure 7.16 (a) In a microwave oven, temperature changes at a constant rate. (b) On the counter or in an oven, temperature changes quickly at first, and then levels off to a final fixed temperature.

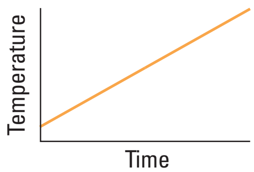
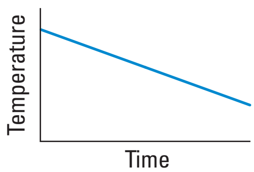
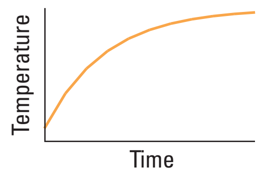
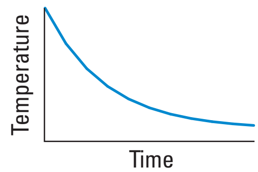
Butter left out on the counter will gradually warm to room temperature; or, if the oven happens to be warm, you can put the butter in there. The warming curves for these options are not straight (Figure 7.16(b)). They rise more quickly at first, when there is a large temperature difference between the butter and its surroundings. The curves eventually level off as the temperature of the butter gets close to the temperature of the air around it.

Cooling curves (starting at a higher temperature and ending at a lower temperature) can also be drawn. Table 7.4 shows the characteristic shapes of graphs for heating and cooling using constant power and for heating and cooling to a fixed temperature.

PHYSICS INSIGHT

Think about heating and cooling curves as you would distance-time graphs. If a temperature-time graph is straight, temperature is changing at a constant rate.

Table 7.4 Two Methods of Heating and Cooling

Heating or Cooling with Constant Power		Heating or Cooling to Fixed Temperature	
Heating	Cooling	Heating	Cooling
			

Concept Check

1. Sketch the heating curves for a cup of cold milk placed
   (a) on the kitchen counter
   (b) in a warm oven
2. Explain the shape of the curves in question 1.
3. Describe how the curves in question 1 differ from each other.

Energy and States of Matter

The energy and organization of the particles in a sample of matter determine the physical state, or **phase**, of the matter: solid, liquid, or gas. Figure 7.17 illustrates the arrangement of water molecules in each state.

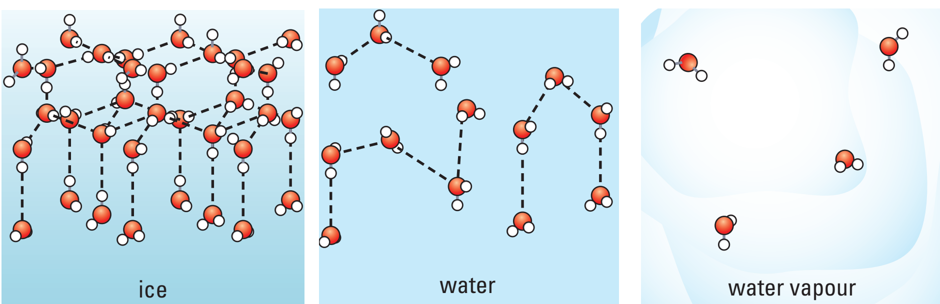


Figure 7.17 The molecules in ice are organized into complex crystal lattices. Each molecule is connected to four others. In liquid water, molecules form bonds, two to three per molecule, that break and reform continually — a liquid does not have a regular structure. In water vapour, the molecules are far apart and not bonded to each other.

The particles in matter are in constant motion and continually transferring energy through collisions. Sometimes a particle gets an exceptional amount of energy, enough to break its bonds with nearby particles. Breaking bonds takes a lot of work. The particle that breaks free loses kinetic energy but gains potential energy as it moves away from its neighbours.

When the temperature of a substance is at the substance's melting or boiling point, a **change of state**, or **phase transition**, begins. The common changes of state caused by transfers of thermal energy are shown in Figure 7.18. Note that melting is also called **fusion**.

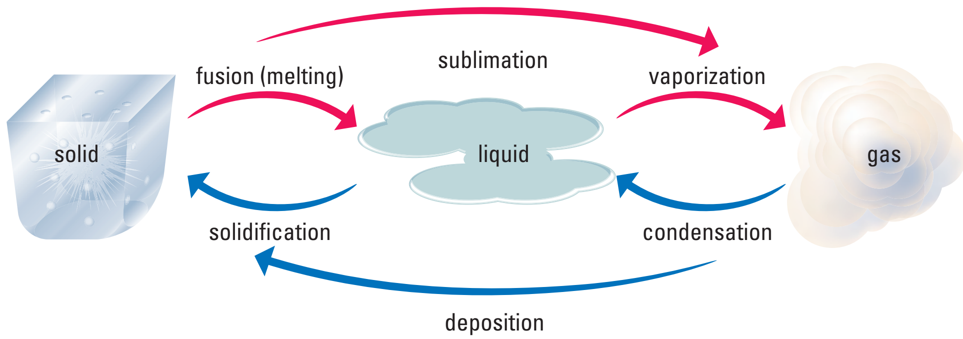
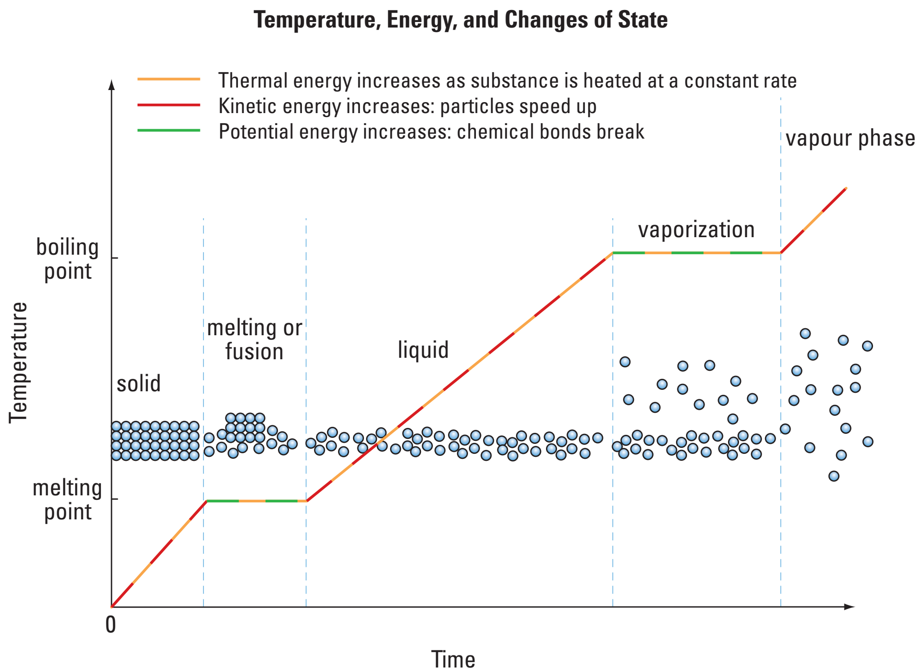


Figure 7.18 Matter can change from one state to another as it is heated or cooled.

Figure 7.19 shows the effect over time of heating a substance at a constant rate. When a solid is heated, the kinetic energy of the vibrating particles increases and the temperature of the substance rises. When the melting point is reached, continued heating causes the bonds between particles to begin to break, and the potential energy of the particles increases. Some of the substance makes a transition to the liquid state.

Figure 7.19 A change in temperature is one indication that thermal energy has been transferred. Another indication of thermal energy transfer is a change of state. During a phase change, potential energy increases but average kinetic energy remains constant, so there is no increase in temperature.



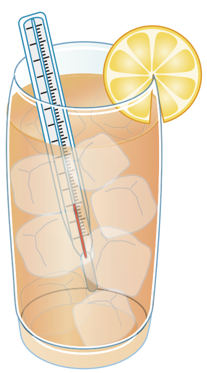


Figure 7.20 A drink with ice remains at 0°C until all of the ice has melted. Only then does the drink start to warm up.

Particles that are now in a liquid state continue to collide with particles in the solid, and they exchange kinetic energy. This keeps the solid and liquid at the same temperature. So, until the change of state is complete, there is no increase in the average kinetic energy of the substance's particles. The temperature does not change during a phase transition, even though thermal energy is transferred (Figure 7.20).

As a liquid is heated, its temperature will rise until it reaches the boiling point. Then, continued heating will cause a transition from the liquid to the vapour phase (Figure 7.21). Once all of the substance has become a vapour, there are no longer any bonds between particles to break. Any additional heating at this point increases the kinetic energy of the particles in the gas, raising its temperature.

When a substance is cooled, energy is removed. The change from gas to liquid occurs at the condensation point, which is the same temperature as the boiling (vaporization) point. The change from liquid to solid occurs at the freezing point, which is the same temperature as the melting point. The temperatures and rates at which phase changes occur depend on the nature of the substance. Only one substance, water, is found as a solid, a liquid, and a gas at ordinary temperatures on Earth's surface. When thermal energy is added to ice, the temperature rises quickly, because the specific heat capacity of ice (2093 J/(kg·K)) is low. The temperature of liquid water rises more slowly because the specific heat capacity of liquid water (4190 J/(kg·K)) is much greater. Liquid water has to absorb more energy for its temperature to rise 1°C than ice does.

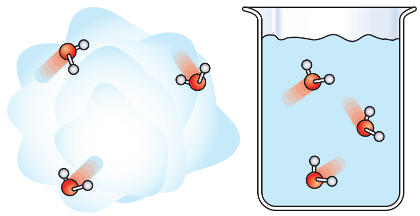


Figure 7.21 At the boiling point, the water molecules in the steam and liquid water have the same kinetic energy. But the molecules in the steam have a lot more potential energy than those in the liquid water, so the steam has more thermal energy than the liquid water.

Concept Check

1. What happens to the particles in a solid when the solid is heated?
2. Describe how kinetic and potential energy change when thermal energy is added to water at its boiling point.
3. Sketch a heating curve for ethanol, which melts at −114°C and boils at 78°C. Label each of the phases and changes of state.

Latent Heat

Latent heat is the thermal energy that is needed for a phase change. *Latent* means "hidden." The increase in thermal energy of the object or system is hidden, because no corresponding change in temperature is observed. The quantity of thermal energy transferred in a phase change from solid to liquid is called the **latent heat of fusion, Q_F**.

Specific Latent Heat of Fusion

The **specific latent heat of fusion**, L_F, of a substance is the quantity of thermal energy needed to melt 1 kg of the substance at its melting point. It is also the quantity of thermal energy that must be removed from 1 kg of the substance to make it freeze or solidify without temperature change. The specific latent heat of fusion is:

$$L_F = \frac{Q_F}{m}$$

where L_F is the specific latent heat of fusion, in kJ/kg, Q_F is the thermal energy transferred, in kJ, and m is the mass of the substance, in kg.

The latent heat of fusion (the quantity of thermal energy transferred during freezing or thawing) is:

$$Q_F = mL_F$$

Notice the similarity of this formula to $Q = mc\Delta T$, the formula for the quantity of thermal energy transferred due to a change in temperature.

A phase change requires a huge amount of energy. For example, the specific latent heat of fusion of water is 333 kJ/kg. It takes 333 kJ of energy to melt 1 kg of ice at 0°C. In comparison, 333 kJ of energy could raise the temperature of 1 kg of water by 80°C.

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Suggested Activity

- C10 Inquiry Activity Overview on page 228

Example 7.4

Gold melts at 1063°C. It takes 3250 J of energy to melt 50.0 g of gold at this temperature. Determine the specific latent heat of fusion of gold.

Given

$Q_F = 3250\ J = 3.250\ kJ$

$m = 50.0\ g = 0.0500\ kg$

Required

specific latent heat of fusion of gold (L_F)

Analysis and Solution

Use the definition of specific latent heat of fusion: $L_F = \frac{Q_F}{m}$.

$$\begin{aligned} L_F &= \frac{Q_F}{m} \\ &= \frac{3.250\ kJ}{0.0500\ kg} \\ &= 65.0\ \frac{kJ}{kg} \end{aligned}$$

Paraphrase

The specific latent heat of fusion of gold is 65.0 kJ/kg.

Practice Problems

1. The melting point of mercury is −38.8°C. When 11.5 kg of frozen mercury at −38.8°C absorbs 138 kJ of thermal energy, all the mercury just melts. What is the specific latent heat of fusion of mercury?
2. The specific latent heat of fusion of silver is 88.0 kJ/kg. How much energy is released when 6.20 μg of silver solidify? ($1\ \mu g = 1 \times 10^{-6}\ g$)
3. Glauber's salt is a hydrated version of sodium sulphate used in glass making. Its specific latent heat of fusion is 241 kJ/kg. It takes 3.71×10^8 J of thermal energy to melt a mass of Glauber's salt at its melting point. Calculate the mass of salt.

Answers

1. 12.0 kJ/kg
2. 5.46×10^{-4} J
3. 1.54 t

Specific Latent Heat of Vaporization

The quantity of thermal energy transferred in a phase change from liquid to gas is called the **latent heat of vaporization, Q_V**. The **specific latent heat of vaporization, L_V**, of a substance is the quantity of thermal energy needed to vaporize 1 kg of the substance at its boiling point. It is also the quantity of thermal energy that must be removed from 1 kg of the substance to make it condense.

The specific latent heat of vaporization is:

$$L_V = \frac{Q_V}{m}$$

where L_V is the specific latent heat of vaporization, in kJ/kg, Q_V is the energy transferred, in kJ, and m is the mass of the substance, in kg.

The latent heat of vaporization (the thermal energy transferred during vaporization or condensation) is:

$$Q_V = mL_V$$

Water has a high specific latent heat of vaporization. It takes 2255 kJ of thermal energy to boil 1 kg of water into steam (Figure 7.22). And when 1 kg of steam condenses back into liquid water, it releases 2255 kJ of energy as heat. This is why even a small amount of steam can cause a much more severe burn to your skin than a burn from hot water. Your skin must remove that entire 2255 kJ per kilogram of heat to condense the steam before the temperature of the steam drops at all.

Figure 7.22 Steam is a transparent gas. When a kettle boils, pure steam emerges right at the spout, and is not visible. The white mist you see consists of tiny droplets of liquid water that have condensed as the hot steam mixes with the cooler air.

Example 7.5

The boiling point of ethanol is 78.4°C. Calculate the quantity of energy needed to completely vaporize 75.0 g of ethanol if its initial temperature is (a) 78.4°C and (b) 22.4°C. The specific latent heat of vaporization of ethanol is 854 kJ/kg and its specific heat capacity is 2.72 kJ/(kg·K).

Given

(a) $m = 75.0 \text{ g} = 0.0750 \text{ kg}$
$L_V = 854 \text{ kJ/kg}$

(b) $T_i = 22.4°\text{C}$
$T_f = 78.4°\text{C}$
$c = 2.72 \text{ kJ/(kg·K)}$

Required

(a) latent heat of vaporization (Q_V)
(b) heat to warm to boiling point and vaporize (Q_{TOT})

Analysis and Solution

(a) Use the formula for latent heat of vaporization.

$$\begin{aligned} Q_V &= mL_V \\ &= (0.0750 \cancel{\text{kg}})\left(854 \frac{\text{kJ}}{\cancel{\text{kg}}}\right) \\ &= 64.05 \text{ kJ} \\ &= 64.1 \text{ kJ} \end{aligned}$$

(b) Calculate the amount of energy needed to warm the ethanol from 22.4°C to 78.4°C.

$$\begin{aligned} Q &= mc\Delta T \\ &= (0.0750 \text{ kg})\left(2.72 \frac{\text{kJ}}{\text{kg·K}}\right)(78.4°\text{C} - 22.4°\text{C}) \\ &= (0.0750 \text{ kg})\left(2.72 \frac{\text{kJ}}{\text{kg·K}}\right)(56.0°\text{C}) \\ &= (0.0750 \cancel{\text{kg}})\left(2.72 \frac{\text{kJ}}{\cancel{\text{kg·K}}}\right)(56.0 \cancel{\text{K}}) \\ &= 11.424 \text{ kJ} \end{aligned}$$

The total energy to warm and vaporize the ethanol is:

$$\begin{aligned} Q_{TOT} &= Q + Q_V \\ &= 11.424 \text{ kJ} + 64.05 \text{ kJ} \\ &= 75.474 \text{ kJ} \\ &= 75.5 \text{ kJ} \end{aligned}$$

Paraphrase

It takes 64.1 kJ of energy to vaporize the ethanol at its boiling point. It takes 75.5 kJ of energy to vaporize the ethanol starting from 22.4°C.

Practice Problems

1. The specific latent heat of vaporization of liquid hydrogen is 452 kJ/kg. How much thermal energy is needed to vaporize 23.7 mg of liquid hydrogen at its boiling point?
2. The boiling point of Freon-12 is −29.8°C. How much thermal energy is absorbed by 455 g of Freon-12 going from the liquid phase at −29.8°C to the gaseous phase at 20.2°C? The specific latent heat of vaporization of Freon-12 is 143 kJ/kg and its specific heat capacity is 950 J/(kg·K).
3. How much thermal energy is needed to turn 15.6 kg of water at 25.0°C into steam at 200.0°C? Check Table 7.1 on page 213 for the specific heat capacities of liquid water and water vapour (steam).

Answers

1. 10.7 J
2. 86.7 kJ
3. 4.32×10^7 J

Concept Check

1. Why is a burn from steam more serious than a burn from boiling water?
2. Explain the difference between latent heat of fusion and specific latent heat of fusion.
3. Describe what happens to the kinetic energy, potential energy, and thermal energy of a substance during vaporization.

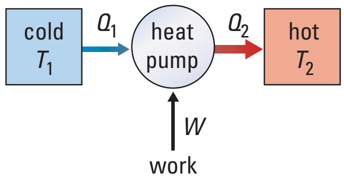

Figure 7.23 A heat pump does work to transfer thermal energy from an area of lower temperature to an area of higher temperature.

Heat Pumps

A refrigerator is a type of heat pump. A **heat pump** transfers thermal energy from a cooler to a warmer place (Figure 7.23). The natural direction for heat to flow is from a warmer to a cooler place, and to reverse this, a heat pump must do work.

Refrigerators and Air Conditioners

Figure 7.24 shows the working parts of a refrigerator. All of the tubing that runs through a refrigerator is made of copper, an excellent conductor of thermal energy. The tubing is filled with a fluid called a **refrigerant**, or coolant, that vaporizes at a low temperature. The cooling process in a refrigerator has four stages:

1. The refrigerant enters the **compressor** as a vapour at about room temperature. Here, an electric motor squeezes the refrigerant. The refrigerant becomes a hot vapour under high pressure.
2. The **condenser** is a set of coils on the back of or under the refrigerator. The refrigerant enters the condenser, where it releases thermal energy by conduction to the air around the refrigerator. As it gives up energy equal to its latent heat of vaporization, it cools and condenses into a warm liquid.
3. The warm liquid refrigerant is then forced through the **expansion valve** as a fine spray, into a region of low pressure. Some of the liquid vaporizes, and the temperature of the liquid–vapour mixture drops very low.
4. The **evaporator** is loops of tubing in the walls of the refrigerator and top of the freezer. Here, thermal energy is conducted from the interior of the fridge, through the tubing, and into the cold refrigerant. Gradually, the refrigerant vaporizes fully, absorbing thermal energy equal to its latent heat of vaporization. This cools the interior of the fridge. The vaporized refrigerant leaves the evaporator and returns to the compressor to continue the cycle. An air conditioner, like a refrigerator, uses an evaporator to cool an area.

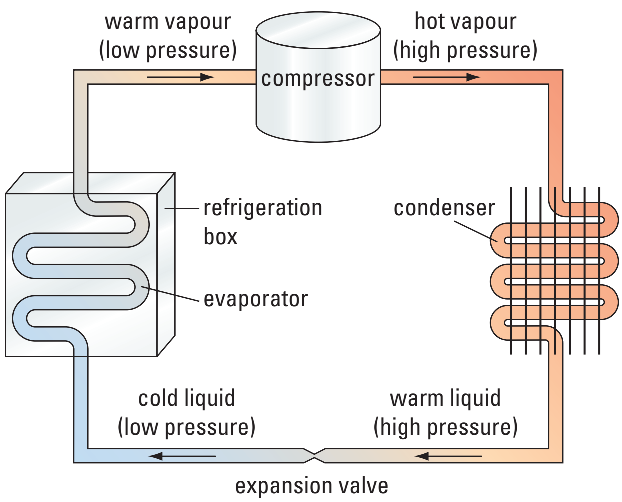

Figure 7.24 A refrigerator cooling circuit

Concept Check

1. List the four main parts of the cooling system in a refrigerator.
2. Why does the refrigerant cool when it goes through the expansion valve?
3. The refrigerant absorbs and then releases its latent heat of vaporization. Where do these transfers of energy occur?

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Explore More

What methods and devices are used to cool materials to cryogenic temperatures?

Air-to-Air Heat Pumps

Another type of heat pump uses the condenser to heat an area. For example, an **air-to-air heat pump** runs between the air outside of a building and the air inside (Figure 7.25). In the winter, it transfers thermal energy from the cooler outside air to the warmer inside air in much the same way as a refrigerator extracts heat from its inside. Unlike the heat generated by a furnace or electric heater, this is heat you don't have to pay for.

Air-to-air heat pumps can extract heat from the air even when the outside temperature is as low as −10°C. Auxiliary heating is required for days below −10°C. In the summer, with the flip of a switch, an air-to-air heat pump runs backward — it becomes an air conditioner pumping heat from inside to outside.

The installation of an air-to-air heat pump is a similar procedure to the installation of a central air conditioner. The technology is used both in new buildings and in renovations of existing buildings.

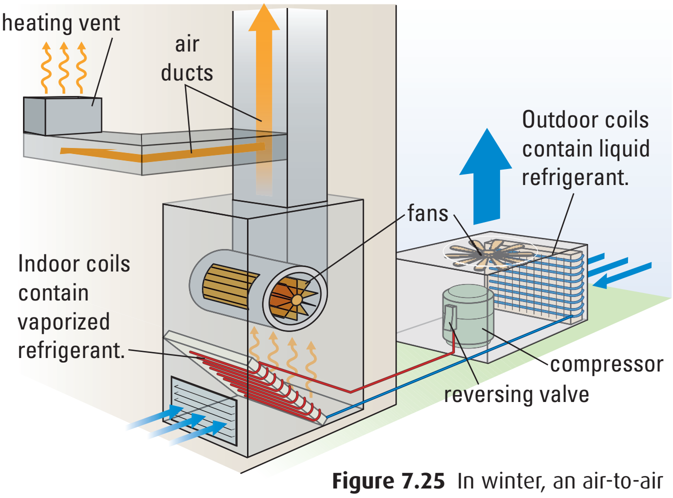


Figure 7.25 In winter, an air-to-air heat pump draws heat from the outside air to heat the home.

Ground Source Heat Pumps

The thermal energy captured by a **ground source heat pump** comes from the ground (or water) near the building being heated. This thermal energy may have come down from the surface or up from deep inside Earth, or a combination of both. In either case, the coolant loops are very close to the surface. Several possible arrangements are shown in Figure 7.26.

The temperature of the ground below the frost line is reasonably constant year round. As a result, in the winter, a ground source heat pump pulls heat from a warmer source than an air-to-air heat pump does, and no auxiliary heat is needed. Ground source heat pumps are most appropriate for new construction, but even there the installation costs of the system are high.

Heating by ground source heat pumps is sometimes called *geothermal heating*. Another version of geothermal heating, discussed in section 7.3, uses energy from far below Earth's surface.

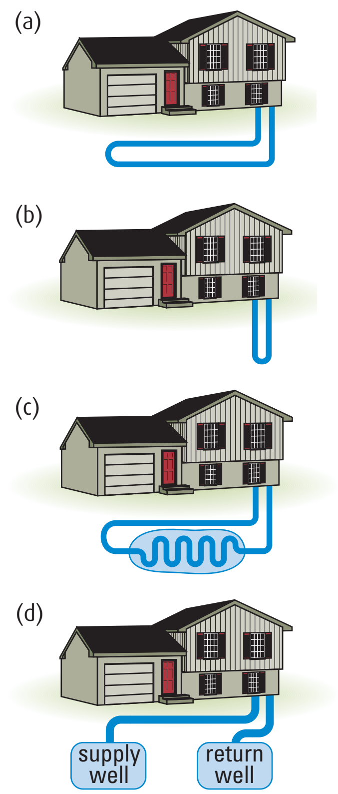


Figure 7.26 Ground source heat pump systems: (a) horizontal loop (b) vertical loop (c) lake or pond loop (d) open system

Refrigerants

The most challenging feature of heat-pump design is the choice of refrigerant. The ideal fluid has the correct physical properties (a low boiling point, high specific heat capacity, and high specific latent heat); it won't pose immediate danger or cause long-term environmental problems if it leaks out; it is plentiful or can be manufactured easily; and it is inexpensive. Some common refrigerants include:

- *Ammonia:* Its fumes are extremely toxic. It continues to be used in industrial refrigeration.
- *Freon and other chlorofluorocarbons*: Chlorofluorocarbons deplete Earth's ozone layer and are thought to contribute to climate change. They are no longer used in new appliances.
- *Propane and butane*: These hydrocarbon refrigerants are explosive and not appropriate for vehicle air conditioning. They are now being used in domestic refrigerators and air conditioners.
- *Anti-freeze*: It has good heat capacity for ground loops but lacks a phase transition for refrigeration. It is toxic in ground water.
- *Water:* It has good heat capacity for ground source systems but lacks a phase transition for refrigeration. It freezes too easily for most Canadian ground source applications.

Chemical engineers are actively researching new alternatives.

PHYSICS•SOURCE

Take It Further

David Willey walks barefoot over hot coals as part of a physics demonstration — and doesn't get burned. Investigate explanations of the physics of fire walking and create a short presentation.

C9 **Inquiry Activity** PHYSICS•SOURCE

REQUIRED SKILLS
- Using appropriate equipment and tools
- Analyzing patterns

Cooling Curve for Water

Question

Does a cup of hot water cool at a constant rate?

Activity Overview

In this activity, you will investigate how the temperature of hot water changes when it is placed in an ice bath. After taking temperature–time data, you will draw a cooling curve. Using both the data and the graph, you will determine whether the water cools slowly and then quickly, at a constant rate, or quickly and then slowly. You will then apply your understanding to other cooling and heating situations.

Your teacher will give you a copy of the full activity.

Prelab Questions

Consider the questions below before beginning this activity.

1. Why does a bowl of hot soup left on a table cool off?
2. Predict which factors will affect the rate of cooling of hot water.
3. How might you check your predictions from question 2?

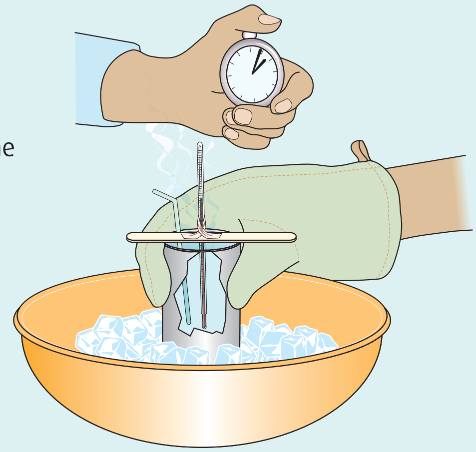


Figure 7.27 You will measure the temperature of the cooling water every 30 s.

C10 **Inquiry Activity** PHYSICS•SOURCE

REQUIRED SKILLS
- Measuring
- Evaluating procedures

Specific Latent Heat of Fusion

Question

How much thermal energy is required to change the phase of water from solid to liquid?

Figure 7.28 When an icicle melts, it absorbs thermal energy equal to its latent heat of fusion.

Activity Overview

Measuring thermal energy transfers precisely is challenging, but an accurate value for the specific latent heat of fusion of a substance is essential for many technologies. In this activity, you will use a calorimeter to measure the specific latent heat of fusion of ice. You will place ice cubes in hot water and find the final temperature of the melted ice-and-water mixture. You will determine L_f for water using the principle of heat exchange and then compare your experimental result with the accepted value.

Your teacher will give you a copy of the full activity.

Prelab Questions

Consider the questions below before beginning this activity.

1. Explain the difference between latent heat of fusion and specific latent heat of fusion.
2. What quantities do you need to know to find the specific latent heat of fusion of a material?
3. Describe how you might measure each of the quantities identified in question 2.

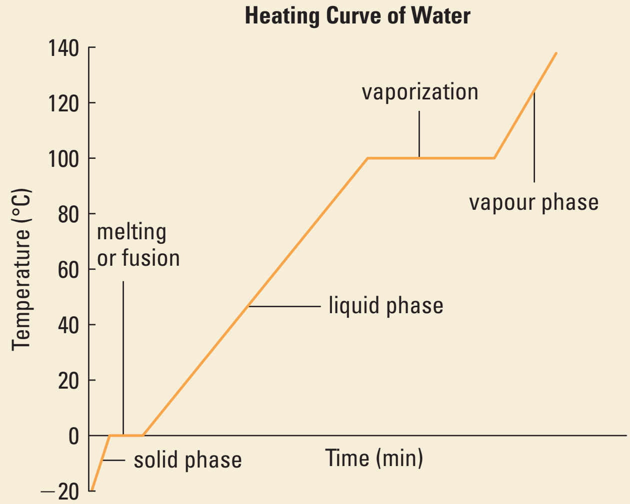
7.2 Check and Reflect

Key Concept Review

1. Sketch a temperature-time graph for each of:
   - a cup of soup in the microwave
   - a cake fresh out of the oven cooling on the window sill
   - a bowl of ice cream sitting on the counter
2. A cooling curve for an object is a straight line. Describe the rate of change of temperature of the object.
3. Explain why a mixture of water and ice stays at 0°C until all of the ice has melted.
4. What does the word "latent" mean in the terms *latent heat* and *specific latent heat*? Why is this meaning appropriate?
5. Explain why you feel cool when water evaporates from your skin.
6. A substance is at its boiling point. Compare the thermal energy of the particles that are in the liquid phase and the particles in the vapour phase.
7. What is a heat pump?
8. Describe the purpose of these parts of a refrigerator: condenser, evaporator, expansion valve, and compressor.
9. In an air conditioner, where is the condenser? Where is the evaporator?
10. What is an air-to-air heat pump?
11. Explain why many new houses are being built with ground source heat pumps.

Connect Your Understanding

12. Look up "specific" in a dictionary. Explain what this word means in the terms *specific heat capacity* and *specific latent heat*.
13. Use the kinetic molecular theory of matter to explain why an object cools quickly if its surroundings are very cold, and cools more slowly when its surroundings are not so cold.
14. As the LHC was assembled, 31×10^3 t of material had to be cooled. In the initial cool-down, 12×10^6 L of liquid nitrogen were vaporized. Calculate the amount of heat absorbed by the liquid nitrogen (L_V = 397 kJ/kg; density = 0.8084 kg/L).
15. Explain what is happening in each section of the heating curve below.



Question 15

16. It takes 323 J of thermal energy to melt 5.13 g of gold at its melting point. Find the specific latent heat of fusion of gold.
17. Ammonia boils at −33°C. Its specific latent heat of vaporization is 1370 kJ/kg. How much thermal energy is released when 12.7 kg of ammonia condense at its boiling point?
18. Calculate the quantity of thermal energy needed to raise the temperature of 650.0 kg of iron from 20°C to its melting point, 1538°C, and then melt it. (*Iron:* c = 452 J/(kg·K), L_F = 247 kJ/kg)
19. Water has high specific heat capacity, specific latent heat of fusion, and specific latent heat of vaporization compared to most other materials. Describe some situations in your life that illustrate this statement.

Reflection

20. What is one thing you learned about thermal energy that you didn't know before starting this section?

For more questions, go to PHYSICS•SOURCE

7.3 Thermal Energy and Electricity Generation

Section Summary

- Heat engines transfer thermal energy between two temperatures to produce mechanical energy.
- Thermal power plants use steam to drive turbines to generate electricity.
- Thermal energy released in cooling processes in thermal plants can be used for heating, either through cogeneration or district heating.
- Fossil-fuel thermal plants involve many energy transfers and transformations and use energy less efficiently than hydroelectric plants or wind farms.
- Solar and geothermal technologies are clean and renewable but less efficient than thermal plants.

Civilizations have burned fuel to cook food and keep warm for hundreds of thousands of years, but only in the last few centuries have we learned how to harness thermal energy to do work. With the advent of the steam engine, factories powered by steam from coal replaced manual and animal labour. Industrial technologies developed, people moved into cities, and our whole way of life changed.

Figure 7.29 Steam trains and steamboats were common in Ontario in the 1800s. A steam locomotive is powered by a steam engine, which is an example of a heat engine.

PHYSICS•SOURCE

Explore More

How do the temperatures of the hot and cold sides of a heat engine affect its efficiency?

Steamboats plied Ontario's rivers and lakes throughout the first half of the 19th century. Steven Leacock's story of the sinking of the steamboat *Mariposa Belle* is one of the best-loved stories in Canadian literature. Then came the steam locomotives, hauling people and goods along rails across Canada from sea to sea (Figure 7.29). There were even steam cars made in Ontario in the 1920s. Today, in Ontario's vacation areas, steam train and steamboat excursions offer a chance to step back in time for a few hours.

A steam engine is an example of a heat engine. A **heat engine** produces mechanical energy from thermal energy. It transfers thermal energy between two temperatures, transforming some of it into mechanical energy to do work (Figure 7.30). The process is less than 50 percent efficient for steam engines that transfer energy between temperatures that are practical to produce.

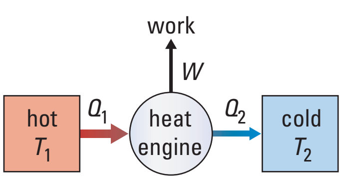


Figure 7.30 A heat engine transfers thermal energy and produces mechanical energy, or work.

Thermoelectric Generation

Currently, about 85 percent of the energy used in the world comes from fossil fuels — coal, oil, and natural gas. About half of these fossil fuels are used for transportation, to heat buildings, and to produce a wide variety of products; the other half are used to generate electricity.

Thermoelectricity is electricity produced directly from heat. In a **thermal power plant**, the turbine is driven by steam. Almost all coal, nuclear, and geothermal power plants, and some natural-gas plants, are thermal plants. About 50 percent of Ontario's electricity is generated by thermonuclear plants and about 25 percent by fossil-fuel plants. Most of Ontario's fossil-fuel plants are coal-fired plants.

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Suggested Activity

- C11 Problem-Solving Activity Overview on page 240

Fossil-Fuel Thermal Plants

In a fossil-fuel thermal plant, electricity generation begins with the burning of the fuel (Figure 7.31). Chemical energy is converted into thermal energy in the combustion gases (mostly carbon dioxide and carbon monoxide), which then heats water in the boiler, changing the water into steam. In the steam drum, the water and steam are separated. The steam is heated until it is very hot **dry steam**, that is, all of its molecules are in the gas state. Many thermal plants use steam that has been heated to 500°C.

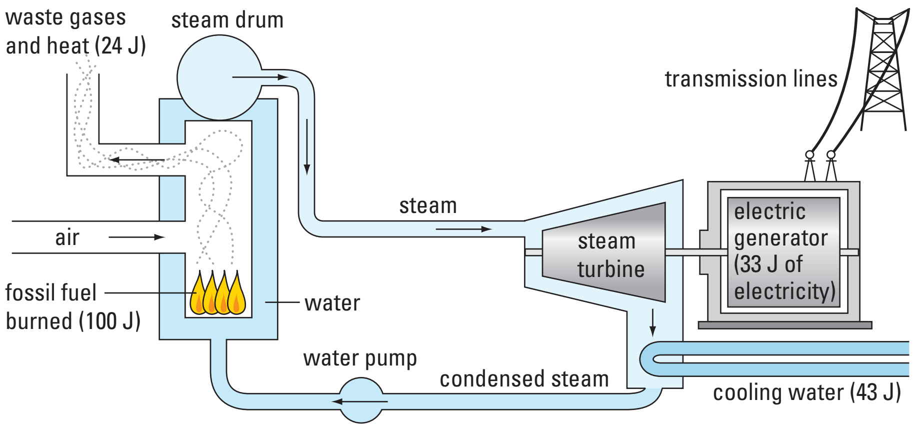

Figure 7.31 In this thermal power plant, burning 100 J of fossil fuel generates 33 J of electricity, for an efficiency of 33 percent.

As the steam is heated, its pressure builds. High-speed jets of steam with a lot of kinetic energy flow through the turbine, turning the turbine blades (Figure 7.32). The thermal energy of the steam has been converted into work: the turbine drives an electric generator that produces electricity. The steam exiting the turbine is cooler. It is condensed by passing around pipes filled with cold water. The condensed steam is finally pumped back to the boiler.

Many energy transformations take place when fossil fuels are burned to generate electricity. As a result, the overall efficiency of thermal power plants is low: 30 percent for older systems and 40 percent for newer designs, as compared with 95 percent efficiency for hydroelectric plants and 45 percent for wind turbines. In the example shown in Figure 7.31, for every 100 J of chemical energy in the fuel, 24 J of thermal energy are transferred to the atmosphere when the hot combustion gases go up the chimney, 43 J of thermal energy are transferred to the cooling water, and only 33 J of electrical energy are generated — 33 J of useful energy from 100 J, or an efficiency of 33 percent.

Figure 7.32 Blades of a steam turbine

Recall that $Efficiency = \frac{\text{energy output}}{\text{energy input}} = \frac{\Delta E_{out}}{\Delta E_{in}}$. This formula can be restated as:

$$Efficiency = \frac{\text{useful energy}}{\text{input energy}} = \frac{\Delta E_{useful}}{\Delta E_{in}}$$

where energy is measured in joules or kilowatt hours. Similarly, the formula $\Delta E = P\Delta t$ can be restated as:

$$\Delta E_{useful} = P_{useful}\Delta t$$

where Δt is the time interval and P_{useful} is the useful (output) power, in watts or kilowatts.

Example 7.6

A thermal power plant is rated at 1000 MW output power and has an efficiency of 40 percent. Determine the quantity of chemical energy used and the quantity of thermal energy released, in kW·h, in 1 year.

Given

$P_{useful} = 1000 \text{ MW}$

$Efficiency = 40\% = 0.40$

$\Delta t = 1 \text{ year}$

Required

input chemical energy (ΔE_{in})

thermal energy released (ΔE_{heat})

Analysis and Solution

Use the relation between energy and power, $\Delta E = P\Delta t$, and the conversion $1 \text{ MW} = 1 \times 10^3 \text{ kW}$ to calculate the useful energy produced.

$$\begin{aligned}\Delta E_{useful} &= P_{useful}\Delta t \\ &= (1000 \text{ MW})(1 \text{ year}) \\ &= \left(1000 \cancel{\text{MW}} \times \frac{1000 \text{ kW}}{1 \cancel{\text{MW}}}\right)\left(1 \cancel{\text{year}} \times \frac{365 \cancel{\text{days}}}{1 \cancel{\text{year}}} \times \frac{24 \text{ h}}{1 \cancel{\text{day}}}\right) \\ &= 8.76 \times 10^9 \text{ kW·h}\end{aligned}$$

Calculate the input energy, ΔE_{in}.

$$\begin{aligned}Efficiency &= \frac{\Delta E_{useful}}{\Delta E_{in}} \\ 0.40 &= \frac{8.76 \times 10^9 \text{ kW·h}}{\Delta E_{in}} \\ (0.40)\Delta E_{in} &= 8.76 \times 10^9 \text{ kW·h} \\ \Delta E_{in} &= \frac{8.76 \times 10^9 \text{ kW·h}}{0.40} \\ &= 2.19 \times 10^{10} \text{ kW·h}\end{aligned}$$

The quantity of thermal energy released is the difference.

$$\begin{aligned}\Delta E_{heat} &= \Delta E_{in} - \Delta E_{useful} \\ &= (2.19 \times 10^{10} \text{ kW·h}) - (8.76 \times 10^9 \text{ kW·h}) \\ &= 1.314 \times 10^{10} \text{ kW·h}\end{aligned}$$

Paraphrase

The quantity of chemical energy used in 1 year is about 2.2×10^{10} kW·h. About 1.3×10^{10} kW·h of thermal energy are released by the plant in a year.

Practice Problems

1. Assume the thermal power plant in Figure 7.31 has an output power of 450 MW.
   (a) Calculate the amount of electrical energy produced each day.
   (b) Calculate the amount of thermal energy that is transferred to the air each day.
2. A coal-fired power plant is rated at 850 MW output power with an efficiency of 36 percent.
   (a) How much chemical energy is transformed by the plant each day?
   (b) The amount of chemical energy contained in coal, or its *energy content*, is 26 MJ/kg. How much coal does the plant need each day?
3. Suppose half of the thermal energy in question 2 can be captured and put to good use. What is the overall efficiency of this modified plant?

Answers

1. (a) 11 GW·h
   (b) 22 GW·h
2. (a) 57 GW·h
   (b) 7.8×10^6 kg
3. 68 percent

Using Waste Heat

Figure 7.33 Pipes used for district heating in Copenhagen, Denmark

Thermal power plants generate at least as much thermal energy as electrical energy. Most of this is released into the environment as waste heat.

Cogeneration is the use of a generating station to generate both electricity and useful thermal energy. Many industrial processes require thermal energy. An industry located close to a thermal power plant can obtain both the electricity and thermal energy it needs from the same source. Several greenhouse operations in Ontario are located close to thermal plants for this reason. Cogeneration works best when small generating facilities are located near where the heat will be used.

District heating is the technology of using thermal energy from a power plant to heat water and buildings nearby. A network of underground pipes distributes steam or hot water to the buildings on the network. Around 150 district heating systems of varying sizes are currently in operation in Canada. The largest one supplies heating to Toronto's downtown core. In Sweden and Denmark, many entire cities use thermal energy from nearby power plants for heating (Figure 7.33). In these countries, steam is a standard utility, just like electricity, gas, and water.

District heating on this scale requires a lot of infrastructure and political will. It is hard to lay insulated pipes under every street unless it is part of a very long-term municipal plan. Buildings must have radiators to use this form of heat. Finally, lifestyle choices play a role: Canadians are not used to having the temperature of their hot water outside their personal control.

District heating is a practical option for new small communities that develop near thermal power plants or industries that produce surplus heat. Many Ontario universities are developing district-heating systems for their offices and residences. Cogeneration and district heating technologies deliver useful heat at little cost and are increasingly being incorporated in large-scale, long-term energy planning and policy, such as Ontario's Green Energy Act of 2009.

Pollution

Figure 7.34 Generating electricity by burning fossil fuels contributes to air pollution and thermal pollution.

Thermal power plants are a major source of pollution (Figure 7.34). The combustion of fossil fuels releases carbon dioxide, carbon monoxide, sulphur dioxide, nitrogen oxides, particulate matter, and volatile organic compounds into the atmosphere, contributing to global warming.

The use of water as a coolant causes **thermal pollution** by increasing the temperature of the water in surrounding lakes. It takes a lot of thermal energy to change the temperature of water, so most aquatic organisms have evolved to survive in narrow temperature ranges. Sudden temperature changes can harm their reproductive cycles, make them more vulnerable to disease, or kill them. Cold water contains more oxygen than warm water, so temperature increases deplete the oxygen available to organisms in the lake. These effects can lead to reduced biodiversity in and around the lake.

Water is a good coolant: it conducts thermal energy well and has a high specific heat capacity. Ontario has plenty of cold water for cooling readily available in the Great Lakes. As a result, Ontario's thermal plants (both fossil fuel and nuclear) are usually located on a lake. Cooling water drawn from the lake absorbs thermal energy from the steam, condensing it to water and cooling it. The cooling water warms and is released back into the lake.

Even though water has a high specific heat capacity, a lot of water needs to flow through the cooling system. To minimize environmental stress on nearby ecosystems, the water returning to the lake must be no more than 10°C warmer than when it left the lake. So, if the lake temperature is 15°C, the returning water must have a temperature of 25°C or less.

Example 7.7

A thermal power plant uses lake water to cool the steam from its turbine. The temperature of the lake water rises by 10°C, absorbing 400 MJ of thermal energy each second. How much lake water is used in (a) 1 s and (b) 1 day?

Given

$Q = 400$ MJ

$\Delta T = 10°C$

$c = 4190$ J/(kg·K)

(a) $\Delta t = 1$ s

(b) $\Delta t = 1$ day

Required

mass of water (a) per second and (b) per day (m)

Analysis and Solution

(a) First, consider a time interval of 1 s. Use the formula for transfer of thermal energy.

$$Q = mc\Delta T$$

$$400 \text{ MJ} = m\left(4190 \frac{\text{J}}{\text{kg·K}}\right)(10°\text{C})$$

$$400 \cancel{\text{MJ}} \times \frac{10^6 \cancel{\text{J}}}{1 \cancel{\text{MJ}}} = m\left(4190 \frac{\cancel{\text{J}}}{\text{kg·}\cancel{\text{K}}}\right)(10 \cancel{\text{K}})$$

$$400 \times 10^6 = m\left(4190 \frac{1}{\text{kg}}\right)(10)$$

$$4.00 \times 10^8 = m\left(\frac{4.190 \times 10^4}{\text{kg}}\right)$$

$$m = \frac{4.00 \times 10^8}{4.190 \times 10^4}\text{kg}$$

$$= 9.55 \times 10^3 \text{ kg}$$

$$= 10 \text{ t}$$

This is the mass of water per second.

(b) Convert seconds to days.

$$9.55 \times 10^3 \frac{\text{kg}}{\text{s}} = 9.55 \times 10^3 \frac{\text{kg}}{\cancel{\text{s}}} \times \frac{3600 \cancel{\text{s}}}{1 \cancel{\text{h}}} \times \frac{24 \cancel{\text{h}}}{1 \text{ day}}$$

$$= 8.25 \times 10^8 \frac{\text{kg}}{\text{day}}$$

$$= 8 \times 10^5 \frac{\text{t}}{\text{day}}$$

Paraphrase

About 10 t of cooling water are used each second, or about 800 000 t of water each day.

Practice Problems

1. A thermal power plant releases 360 MJ of thermal energy into lake water, raising its temperature by 8.0°C. How much water is used each second?
2. A thermal power plant generates 680 kW of output power at an efficiency of 40 percent. Half of the released heat goes into a lake-water cooling system that raises the coolant temperature by 10°C. How much cooling water is needed each second?
3. A thermonuclear plant produces 3.0 GJ of thermal energy and 1.0 GJ of electrical energy per second. The thermal energy is transferred to 84 t of lake water each second. What is the temperature increase in the water?

Answers

1. 11 t per second
2. 12 kg per second
3. 8.5°C per second

Concept Check

1. How is a thermal power plant similar to a hydroelectric plant?
2. What are the main reasons for the low efficiency of a thermal power plant?
3. Explain how fossil-fuel thermal power plants create pollution.

Solar Power

Solar energy — radiant energy from the Sun — is the largest basic energy resource on Earth. Even in northern climates, solar energy can be used to reduce the use of scarce, expensive, and polluting resources.

Insolation is the intensity of solar radiation on a surface, often measured in watts per square metre (W/m^2). At the outer limits of the atmosphere, the insolation is about 1400 W/m^2. On average, about 700 W/m^2 of solar radiation reach the surface of Earth. Notice that the units of insolation are those of *power* per unit *area:*

$$Insolation = \frac{Power}{Area} = \frac{P}{A}$$

An insolation of 700 W/m^2 means that 700 J of solar energy strike each square metre of ground each second.

The Sun only shines for part of a 24-h day, so the full daily amount of solar energy received on a surface depends on the length of time the surface receives light. Suppose the roof of a house receives an insolation of 700 W/m^2 for 8.0 h daily. How much energy (per unit area) is incident on the roof in a 24-h day?

Recall the relationship between energy and power, $\Delta E = P\Delta t$.

Thus, the energy per unit area is related to the power per unit area:

$$\begin{aligned}\frac{\Delta E}{A} &= \frac{P}{A}\Delta t \\ &= Insolation \times \Delta t \\ &= \left(700\ \frac{\mathrm{W}}{\mathrm{m}^2}\right)(8.0\ \mathrm{h}) \\ &= \left(700\frac{\cancel{\mathrm{W}}}{\mathrm{m}^2} \times \frac{1\ \mathrm{kW}}{1000\ \cancel{\mathrm{W}}}\right)(8.0\ \mathrm{h}) \\ &= 5.6\ \frac{\mathrm{kW{\cdot}h}}{\mathrm{m}^2}\end{aligned}$$

The roof receives 5.6 $kW{\cdot}h/m^2$ per day of solar energy — each square metre of roof soaks up 5.6 $kW{\cdot}h$ of free energy each day.

The actual quantity of solar energy that can be captured on a surface depends on the latitude, tilt of the surface, time of day, weather, and season. The **mean daily global insolation** at a given location is the insolation averaged over day and night, varying cloud conditions, and the seasons. The mean daily global insolation for most of Ontario is about 4.2 $kW{\cdot}h/m^2$ per day. This is close to the value found in the calculation above. Figure 7.35 shows the mean global daily insolation for Canada and the United States. Notice the high insolation in Arizona, Nevada, and California.

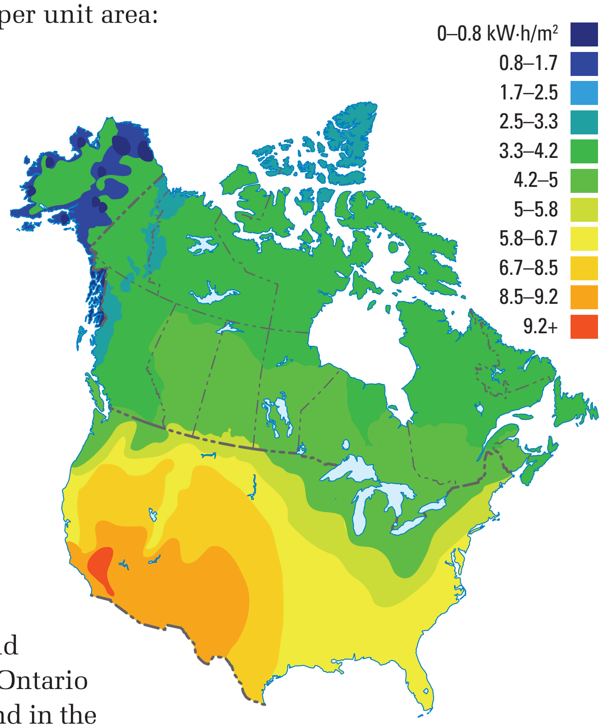

Figure 7.35 Mean daily global insolation for Canada and the United States.

Concept Check

1. Explain why each of the following factors affects insolation: time of day, weather, time of year, and latitude.
2. What is meant by *mean daily global insolation*?
3. Why are many solar technologies being developed and tested in the U.S. southwest?

PHYSICS•SOURCE

Explore More

What methods other than solar cells are used to transform solar energy into electricity?

Photovoltaic Cells

A **solar cell** or **photovoltaic cell** transforms solar energy directly into electricity (Figure 7.36). A solar cell is composed of two layers of silicon. One layer has added phosphorus and the other has added boron. When light strikes the silicon layers, the phosphorus layer becomes negatively charged and the boron layer becomes positively charged. The contact layers on the outside act as positive and negative terminals, allowing you to run an electrical device or store electrical energy in a battery.

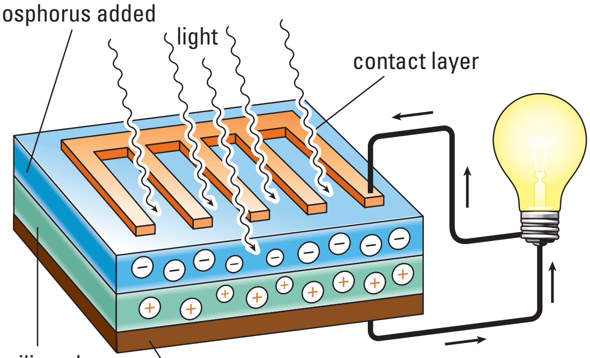

Figure 7.36 A cross-section of a solar cell illustrating the build-up of charges on the silicon layers. Assemblies of solar cells are used to make solar panels.

Solar cells are relatively expensive to make and have an efficiency of about 12 percent. In Canada, where insolation is low, most solar cells are used for off-grid power generation. In sunnier parts of the world, solar cells are used in the thousands in huge solar power plants like the one shown in Figure 7.37.

It currently takes from 15 to 20 years to recoup the costs of a photovoltaic system. As the price of solar cells comes down, and as the number of electricity utilities willing to buy surplus electricity from individual producers grows, the market for solar cells is expected to increase.

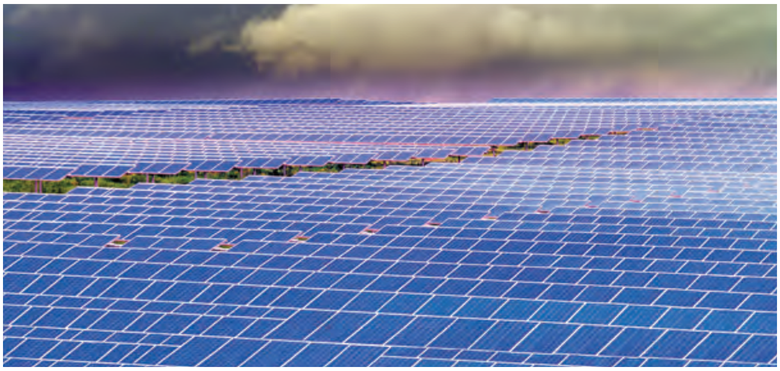

Figure 7.37 Portugal has the most abundant sunlight in Europe and some of the world's largest photovoltaic power stations, with capacities of up to 62 MW. At the one shown here, the Central Solar de Serpa, over 50 thousand solar panels generate 11 MW of electricity. In the United States, solar farms with capacities of up to 600 MW are in development.

Example 7.8

A solar photovoltaic panel is rated at 160 W maximum output power. It measures 1580 mm by 808 mm.

(a) Calculate the maximum output power per square metre.

(b) If this maximum power occurs when the insolation is 700 W/m², find the efficiency of the panel.

Given

$P = 160 \text{ W}$

$l = 1580 \text{ mm} = 1.580 \text{ m}$

$w = 808 \text{ mm} = 0.808 \text{ m}$

$Insolation = 700 \text{ W/m}^2$

Required

(a) power per square metre (P/A)

(b) efficiency (*Efficiency*)

Analysis and Solution

(a) Calculate the area, A, of one panel, and then calculate P/A.

$$A = l \times w = (1.580 \text{ m})(0.808 \text{ m}) = 1.27664 \text{ m}^2$$

$$\frac{P}{A} = \frac{160 \text{ W}}{1.27664 \text{ m}^2} = 125.33 \text{ W/m}^2 = 125 \text{ W/m}^2$$

(b) Compare the useful maximum power per unit area to the insolation.

$$Efficiency = \frac{\text{Power output}}{\text{Power input}} = \frac{\left(\frac{P}{A}\right)}{Insolation} = \frac{125.33 \text{ W/m}^2}{700 \text{ W/m}^2} = 0.179$$

Paraphrase

The maximum power density of the panel is 125 W/m², giving the panel an efficiency of 0.179 or 17.9 percent.

Practice Problems

1. Solar panels measuring 1290 mm by 991 mm are rated at 187 W.
   (a) Calculate the power per unit area for these panels.
   (b) Determine the quantity of electrical energy, in kW·h, generated by one panel at 12 h per day for a year.
2. Fifty percent of a 20-ha solar farm in Texas is covered by panels with the same area and power output as those in question 1. Find the power output of the farm. Note: 1 hectare (ha) = 1×10^4 m².
3. A solar panel has an area of 1.25 m² and an efficiency of 21.0 percent. Find its output power if the insolation is 650 W/m².

Answers

1. (a) 146 W/m²
   (b) 8.2×10^2 kW·h
2. 15 MW
3. 171 W

Solar Collectors

Canadians spend most of their household energy budget on heating the space inside their homes and heating water. **Active solar systems** use mechanical or electrical technologies to convert sunlight into usable energy. **Flat-plate solar collectors** (Figure 7.38), which preheat water for domestic use, are an example of an active solar system. These solar panels can be used in new construction and in renovations, and they can halve a household's hot water costs: it takes from 6 to 13 years to recoup the cost of the panels through savings in electricity costs, compared with 12 to 20 years if you heat water with natural gas.

Figure 7.38 Flat-plate collectors are the most common type of solar collectors used in solar water-heating systems in homes.

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Suggested Activity

- C12 Inquiry Activity Overview on page 240

Figure 7.39 shows how radiant energy is transferred to preheat water in a flat-plate solar collector.

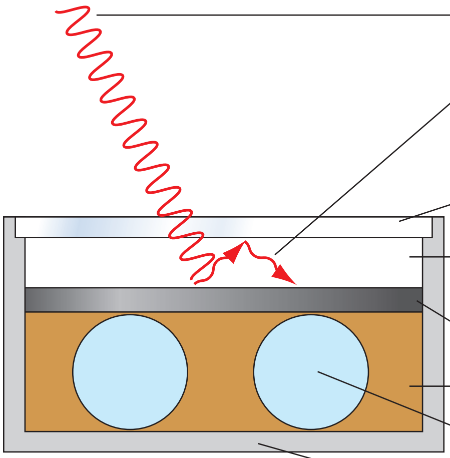

Figure 7.39 A cross-section of a solar flat-plate collector

Passive solar design is a way of planning a building to absorb as much direct sunlight inside as possible in the winter — and as little as possible in the summer. Good passive design includes excellent insulation and windows and inside materials with high heat capacities. Some aspects of passive design can be used in renovation, but it is most effective to incorporate it into new buildings. Even at northern latitudes, passive solar homes can be built that need no auxiliary heating.

Concept Check

1. Describe the energy transformations in a photovoltaic cell.
2. Describe the energy transformations in a flat-plate solar collector.
3. Why may solar hot-water heating be an appropriate technology for Ontario?

Geothermal Power

Geothermal energy is thermal energy that comes from deep inside Earth. Some of this energy is primordial, energy in Earth's core left over from when Earth was formed. Some of the energy comes from the radioactive decay of heavy elements present in the materials that made Earth. Early in Earth's history, its crust solidified, and the core was insulated from space. As a result, the molten core is still very hot — over 4000°C. In places where the crust is thin and there is evidence of significant seismic activity — volcanoes, geysers, and hot springs — geothermal technologies can be used.

Iceland is so volcanically active that there is an abundance of naturally heated water waiting to be tapped (Figure 7.40). Icelandic engineers set up the world's first geothermal district heating system in the 1930s. Today, more than half of the population has access to district heating, and geothermal power plants generate enough electricity for the whole nation.

Figure 7.40 The many hot springs and active volcanoes in Iceland guarantee a constant supply of hot water.

Most of Earth, including most of Ontario, has a thick, stable crust. Very little geothermal energy comes through the surface: about 0.06 W/m^2. Nevertheless, many technologies for geothermal power generation are under development in various parts of the world. The local geology determines which method is most appropriate.

- *Hot water reservoirs:* Geothermal plants built over hot-water reservoirs such as hot springs are the most common way to harness geothermal energy to create electricity.
- *Dry steam reservoirs:* Dry steam trapped underground is ideal for power generation, since the steam can drive a turbine directly. Unfortunately, these sites are rare, and the dry steam is not very hot. The Geysers geothermal power field in California uses steam at just 200°C. As a result, its efficiency is only 15 to 20 percent.
- *Wet steam reservoirs:* These geothermal power fields are found in many countries. Water trapped under pressure doesn't boil, but reaches temperatures of about 175°C. If the pressure is allowed to drop suddenly, the water *flashes* — it very quickly turns into steam. This is the basis of a flash-steam power plant. The quickly vaporizing water drives a turbine that generates electricity. Wet steam is steam with a temperature between 100°C and 200°C.
- *Hot dry rock*: An underground region of hot fractured rock can be used to create steam to drive a steam turbine (Figure 7.41). Sometimes, as in the Steamboat Springs Geothermal Field in Nevada, blasting is used to create more fractures and better flow rates in the hot rock.

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Take It Further

Architects interested in environmentally friendly housing are combining passive solar design with the benefits of being underground (or at least half buried in a hillside). Research the benefits of passive design and underground design. Sketch plans for a small house that is partly underground.

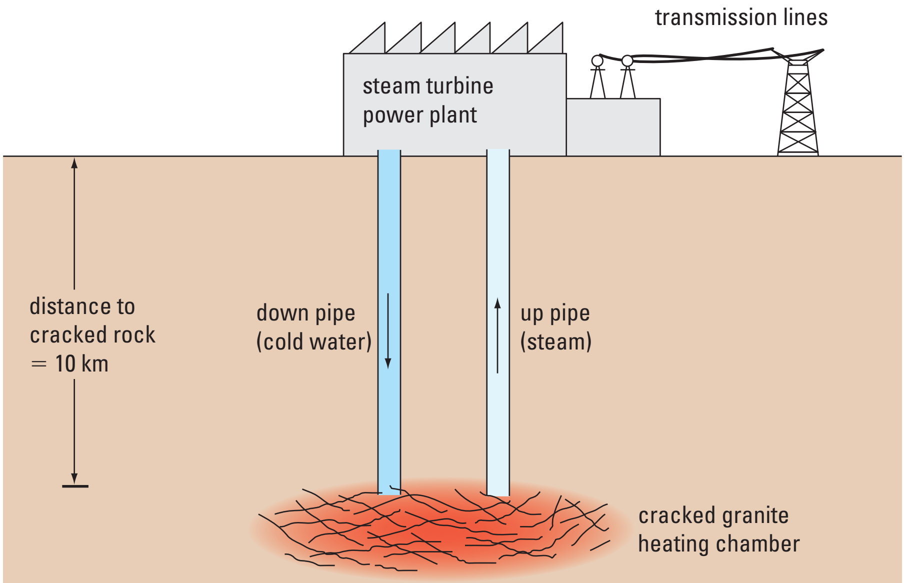

Figure 7.41 A hot rock geothermal power plant

Concept Check

1. Explain the difference between a ground source heat pump and the geothermal technologies described here.
2. Why is Ontario not a favourable location for deep geothermal energy?
3. Describe how a hot spring could be used for cogeneration or district heating.

C11 Problem-Solving Activity

PHYSICS•SOURCE

REQUIRED SKILLS
- Prioritizing and selecting solutions
- Explaining solutions

Build a Steamboat

Problem

How do you build a boat that uses a burning candle as its energy source?

Activity Overview

You will construct a steamboat, similar to the boat in Figure 7.42, that can travel in a straight line on water for approximately 15 cm. After building and testing a prototype model, you will alter the basic design to improve the performance of the boat. You will analyze your modifications and explain how they affected the operation of your steamboat.

Your teacher will give you a copy of the full activity.

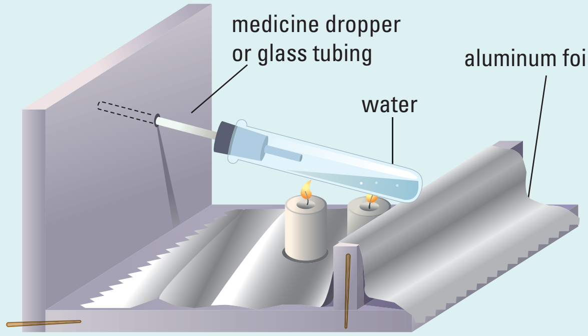

Figure 7.42 Steam-powered boat

Prelab Questions

Consider the questions below before beginning this activity.

1. If you inflate a balloon and then release it, the balloon flies away. Explain why.
2. Describe another situation where a fluid moving in one direction propels an object in the opposite direction.

C12 Inquiry Activity

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REQUIRED SKILLS
- Designing an experimental procedure
- Drawing conclusions

Flat-Plate Solar Collector

Question

What features does a flat-plate solar collector require to optimally trap thermal energy?

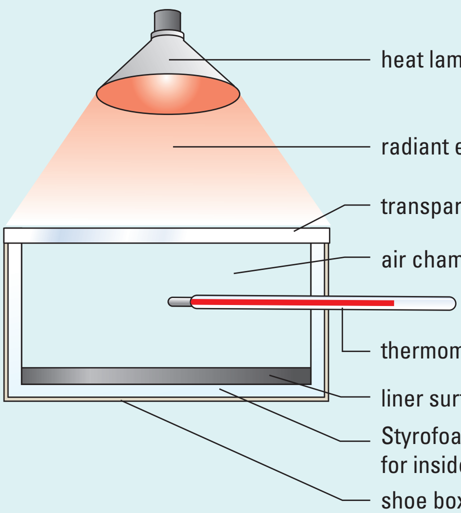


Figure 7.43 Model of a flat-plate solar collector

Activity Overview

In this activity, you will model a solar collector using an open shoe box and a variety of transparent, absorptive, and reflective materials. You will simulate the Sun with a lamp shining into your collector. You will investigate how the choice of the flat plate (the top of the box) affects the temperature increase inside the box. You will also determine what material is most appropriate for the lower inside surface of the collector.

Your teacher will give you a copy of the full activity.

Prelab Questions

Consider the questions below before beginning this activity.

1. What form does energy from the Sun have when it strikes the roof of a house?
2. Describe how sunlight can warm the inside of a car on a cold day.
3. Give an example of the greenhouse effect.

7.3 Check and Reflect

Key Concept Review

1. Describe the main parts of a thermal power plant.
2. In which parts of a thermal power plant is thermal energy produced?
3. What is the typical efficiency of a thermal power plant?
4. How is the steam in the steam condenser cooled in most thermal power plants in Ontario?
5. What is cogeneration? What are its advantages and disadvantages?
6. What is district heating? Why is this technology difficult to implement?
7. Explain the difference between insulation and insolation.
8. (a) Which region of Canada is best suited for large-scale solar power generation?
   (b) Which region of the U.S. is best suited for large-scale solar power generation?
9. Which solar technologies are most suitable for Ontario? Explain.
10. Where does geothermal energy come from?

Connect Your Understanding

11. Why is there a limit on the temperature change allowed for lake water used for cooling? Describe some possible consequences if this limit were not respected.
12. Explain why both fossil-fuel power plants and nuclear power plants need to deal with waste thermal energy.
13. Explain why photovoltaic panels are an appropriate energy source for space stations and inaccessible spacecraft.
14. The new gas-fired combined-cycle power plant in Halton Hills, Ontario, is designed to generate 631.5 MW of output electrical power. It is expected to be about 80 percent efficient. If it runs continuously, how much thermal energy will it produce in a day?
15. A traditional thermal power plant generates 250 MW of output electrical power. It is 40 percent efficient.
    (a) Calculate the rate of chemical energy consumption.
    (b) Calculate the rate of thermal energy production.
    (c) If 60 percent of the waste thermal energy is transferred to lake water, raising the water temperature by 10°C, how much water passes through the plant in 24 h of continuous use?
16. Calculate the efficiency of a photovoltaic solar panel that measures 1195 mm by 541 mm and produces 80 W output power when the insolation is 700 W/m^2.
17. Which of the technologies in this section do you think will increase in use in the next 10 to 20 years? Explain your reasoning.

Reflection

18. What do you think is the most interesting information that you learned in this section?

Question 13 Solar panels on the International Space Station

For more questions, go to PHYSICS•SOURCE

CHAPTER 7 CHAPTER REVIEW

Key Concept Review

1. Describe the kinetic molecular theory of matter.
2. What types of particles occur in matter?
3. Describe three possible motions of particles in matter.
4. Explain the difference between thermal energy and heat.
5. Why does heat move from warmer materials to cooler materials?
6. Which has a higher heat capacity: an ice cube or a large block of ice? Explain.
7. Which has a higher specific heat capacity: an ice cube or a large block of ice? Explain.
8. Describe how a calorimeter prevents heat loss. Why is this important?
9. You move a hot glass baking dish from the oven to a rack on the kitchen counter. Sketch the cooling curve for the glass dish. Explain the shape of the curve.
10. Sketch the warming curve for a bowl of soup in a microwave oven. Explain the shape of the curve.
11. Sketch a graph for hot steam cooling to ice. Label the states of water and the changes of state.
12. Define the *latent heat of fusion* of a material.
13. Define the *specific latent heat of vaporization* of a material.
14. Explain the difference between the latent heat and specific latent heat of a phase transition.
15. What is a heat pump? Give an example of a heat pump.
16. Where is the condenser in the following devices: a refrigerator, air conditioner, and air-to-air heat pump (in winter mode)?
17. What is a heat engine? Give an example of a heat engine.
18. Describe how the energy in a fossil fuel is transformed into electrical energy in a thermal power plant.
19. At which two steps in the process of generating thermoelectricity is a great quantity of heat lost?
20. Describe two types of pollution associated with thermal power plants.
21. What is *cogeneration*? How can it improve the overall efficiency of a thermal power plant?
22. How can solar energy be converted directly into electricity?
23. How can solar energy be converted directly into heat for water heating?
24. Explain the two meanings of *geothermal energy*.
25. Which type of geothermal energy is being used in Ontario?

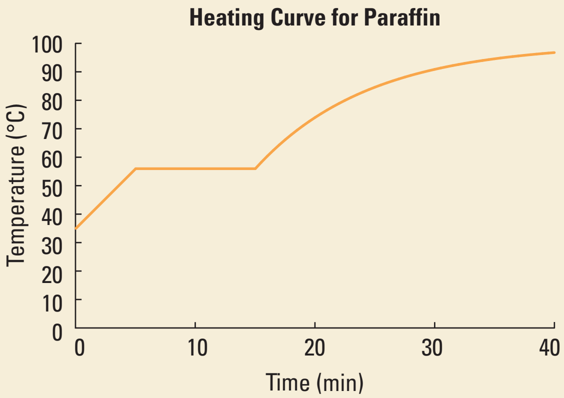
Connect Your Understanding

26. Describe how radiation, conduction, and convection each contribute to heating a cup of noodle soup in a microwave oven.
27. Use the kinetic molecular theory of matter to explain why a hot aluminum rack cools more quickly than a hot block of aluminum with the same mass.
28. How much thermal energy must be added to a 675-g bar of gold to raise its temperature from 20°C to its melting point, 1063°C?
29. (a) The specific heat capacity of olive oil is 1970 J/(kg·K). Determine the final temperature if 185 g of olive oil at 41.2°C is mixed with 122 g of olive oil at 19.6°C.
    (b) Explain why you do not need to know the specific heat capacity of olive oil to solve this question.
30. (a) When 1.73 kg of ethylene glycol (antifreeze) at 11.6°C are mixed with 1.42 kg of water at 40.4°C, the final temperature is 29.2°C. Find the specific heat capacity of ethylene glycol.
    (b) What assumptions did you make to solve this problem?
31. Some milk at 10.2°C is added to 231 g of milk at 86.9°C. The final temperature of the mixture is 72.4°C. What mass of cold milk was used?

ACHIEVEMENT CHART CATEGORIES

[k] Knowledge and understanding [t] Thinking and investigation
[c] Communication [a] Application

32. A chunk of paraffin wax is placed in a test tube. The test tube is supported in a boiling water bath. The heating curve for the paraffin is shown below.



Question 32

(a) What is happening between t = 5 min and t = 15 min? [c]
(b) What is happening between t = 15 min and t = 40 min? [c]
(c) Why does the curve level off between t = 15 min and t = 40 min? [t]

33. It takes 1.18 J of thermal energy are vaporize 432 mg of mercury. Find the specific latent heat of vaporization of mercury. [a]

34. The specific heat capacity of liquid ammonia is 4700 J/(kg·K) and its specific latent heat of vaporization is 1370 kJ/kg. Determine the amount of thermal energy needed to raise the temperature of 745 g of liquid ammonia from −70.0°C to its boiling point, −33.5°C, and then vaporize it completely. [a]

35. When 16.2 MJ of thermal energy are added to 43.7 kg of ice at 0.00°C, all of the ice melts. Find the final temperature of the melt water if no heat escapes. Use L_F of water = 333 kJ/kg. [t]

36. (a) Explain why refrigeration and cooling devices are important in our society. [c]
(b) Describe some of the hazards associated with cooling technologies. [c]

37. A fossil-fuel thermal power plant produces 7.6 TW·h of electrical energy and 13.5 TW·h of thermal energy each year. Find: [a]
(a) the annual amount of input chemical energy
(b) the plant's efficiency

38. A coal-fired thermal power plant is rated at 1100 MW with an efficiency of 45 percent. Calculate the daily amount (in MW·h) of: [a]
(a) output electrical energy
(b) input chemical energy
(c) thermal energy

39. A thermal power plant discharges 800 MW of waste heat into a nearby lake. The temperature of the cooling water rises 8.5°C. What mass of water passes through the plant each second? [a]

40. Typical insolation on a sunny day is 700 W/m^2. Explain the choice of scientific units. [c]

41. The mean daily global insolation in Ontario is 4.2 kW·h/m^2 per day. Explain why this is a measure of power per unit area. [c]

42. Choose a household appliance that uses the transformation of thermal energy; for example, a toaster or dehumidifier. Describe the types of energy that are involved in its operation, and how the energy transformations occur. [c]

43. Explain the difference between the physics meaning of "conservation of energy" and the environmental/societal meaning of "conservation of energy." Illustrate your explanation with examples. [c]

Reflection

44. Describe what you found most challenging in learning about thermal energy and changes of state. [c]

Unit Task Link

Many new and not-so-new technologies can provide heat and electricity to remote places. Your task is to research how to meet the energy needs of the remote retreat centre. You may find it helpful to group those systems and devices that require electricity (for example, a computer) and those that could be powered in another way (for example, a stove). Research the advantages and disadvantages of the technologies that produce electricity and those that produce heat.

For more questions, go to PHYSICS•SOURCE