Heat Capacity

6.3

Have you ever warmed up a pot of water on a stove to make soup? If so, you may have noticed that it takes a relatively long time for the water to warm up. However, if you tried to warm up the same amount of oil in the same heating conditions you would notice that the oil warms up faster. Conversely, if a pot of water and a similar pot of oil at the same temperature are left on a stove to cool down, the oil will cool down faster than the water. Why do different substances warm up and cool down at different rates?

Specific Heat Capacity

It takes more energy to increase the temperature of 1.0 kg of water by 1 °C than it takes to increase the temperature of 1.0 kg of vegetable oil by 1 °C. The amount of energy needed to raise the temperature of 1 kg of a substance by 1 °C is called the **specific heat capacity (*c*)** of the substance.

specific heat capacity (*c*) the amount of energy, in joules, required to increase the temperature of 1 kg of a substance by 1 °C; units are J/(kg•°C)

The specific heat capacity of water is 4.18×10^3 J/(kg·°C), which is high in comparison with many other common liquids. The specific heat capacity of water indicates that it takes 4.18×10^3 J of energy to raise the temperature of 1 kg of water by 1 °C. Vegetable oil has a specific heat capacity of 2.0×10^3 J/(kg·°C), indicating that it takes approximately half as much energy to heat up 1 kg of vegetable oil by 1 °C than it takes to heat up 1 kg of water by 1 °C. So, a pot containing 1 kg of water at 10 °C uses a little more than twice as much energy to reach 100 °C as a pot containing 1 kg of vegetable oil at 10 °C. This difference occurs because water and vegetable oil are composed of different types of molecules. Different molecules require different amounts of energy to increase their kinetic energies by the same amount. Specific heat capacity also represents how much thermal energy is released when a substance cools down by 1 °C. **Table 1** gives the specific heat capacities of some common substances.

Table 1 Specific Heat Capacities of Common Substances

Substance	Specific heat capacity (J/(kg·°C))
water	4.18×10^3
ethyl alcohol	2.46×10^3
ice	2.1×10^3
aluminum	9.2×10^2
glass	8.4×10^2
iron	4.5×10^2
copper	3.8×10^2
silver	2.4×10^2
lead	1.3×10^2

Quantity of Heat

The total amount of thermal energy transferred from a warmer substance to a colder substance is called the **quantity of heat (*Q*)**. A quantity of heat calculation takes into account the mass (m) of the substance, the specific heat capacity (c) of the substance, and the change in the temperature (ΔT) that the substance undergoes as it heats up or cools down. The quantity of heat is measured in joules and can be calculated using the equation

quantity of heat (*Q*) the amount of thermal energy transferred from one object to another

$$Q = mc\Delta T$$

where Q is the quantity of heat in joules, m is the mass of the object in kilograms, c is the specific heat capacity of the substance in joules per kilogram degree Celsius, and ΔT is the change in temperature in degrees Celsius. The change in temperature (ΔT), is calculated by subtracting the initial temperature (T_1) of the substance from its final temperature (T_2) using the equation

$$\Delta T = T_2 - T_1$$

Note that if an object absorbs energy, its final temperature is greater than its initial temperature, and the value of ΔT is positive. However, if an object releases thermal energy, its final temperature is lower than its initial temperature, and the value of ΔT is negative. The following Tutorial demonstrates how to use the quantity of heat equation to calculate the amount of thermal energy absorbed by an object. The Tutorial also shows how to calculate the mass of an object or the specific heat capacity of an unknown object.

Tutorial 1 Quantity of Heat Calculations

The quantity of heat equation $Q = mc\Delta T$ can be used to calculate the quantity of thermal energy gained or lost by an object.

Sample Problem 1

When 200.0 mL of water is heated from 15.0 °C to 40.0 °C, how much thermal energy is absorbed by the water?

Since the quantity of heat equation is based on the mass of an object, we must first determine the mass, in kilograms, of 200.0 mL of water. To do this, we use the density of water, which is 1.0 g/mL. We then calculate the change in the temperature of the water using the equation $\Delta T = T_2 - T_1$. Finally, we use the quantity of heat equation, $Q = mc\Delta T$, along with the mass of the water, m, the specific heat capacity of water, c_W, and the change in temperature of the water, ΔT, to determine how much thermal energy is absorbed by the water.

Given: $V = 200.0$ mL; $T_1 = 15.0$ °C; $T_2 = 40.0$ °C; $c_W = 4.18 \times 10^3$ J/(kg•°C)

Required: Q

Analysis: $\Delta T = T_2 - T_1$; $Q = mc\Delta T$

Solution:

$$m = 200.0\ \cancel{\text{mL}} \times \frac{1\ \cancel{\text{g}}}{1\ \cancel{\text{mL}}} \times \frac{1\ \text{kg}}{1000\ \cancel{\text{g}}}$$

$$m = 0.2000\ \text{kg}$$

$$\Delta T = T_2 - T_1$$

$$= 40.0\ °\text{C} - 15.0\ °\text{C}$$

$$\Delta T = 25.0\ °\text{C}$$

Now that we have calculated the mass of the water in kilograms and the change in temperature, we may use these values to calculate the quantity of heat:

$$Q = mc\Delta T$$

$$= (0.2000\ \cancel{\text{kg}})\left(4.18 \times 10^3\ \frac{\text{J}}{\cancel{\text{kg}}\cdot\cancel{°\text{C}}}\right)(25.0\ \cancel{°\text{C}})$$

$$Q = 2.09 \times 10^4\ \text{J}$$

Statement: The water absorbs 2.09×10^4 J of thermal energy.

Sample Problem 2

An empty copper pot is sitting on a burner. The pot has a mass of 1.2 kg and is at a temperature of 130.0 °C. If the pot cools to a room temperature of 21.0 °C, how much thermal energy does it release to the surroundings?

From Table 1 on page 281, we can determine that the specific heat capacity of copper is 3.8×10^2 J/(kg•°C). As in Sample Problem 1, we need to find the change in temperature before calculating the quantity of thermal energy released by the pot using the quantity of heat equation.

Given: $m = 1.2$ kg; $T_1 = 130.0$ °C; $T_2 = 21.0$ °C; $c = 3.8 \times 10^2$ J/(kg•°C)

Required: Q

Analysis: $\Delta T = T_2 - T_1$; $Q = mc\Delta T$

Solution:

$$\Delta T = T_2 - T_1$$

$$= 21.0\ °\text{C} - 130.0\ °\text{C}$$

$$\Delta T = -109\ °\text{C}$$

$$Q = mc\Delta T$$

$$= (1.2\ \cancel{\text{kg}})\left(3.8 \times 10^2\ \frac{\text{J}}{\cancel{\text{kg}}\cdot\cancel{°\text{C}}}\right)(-109\ \cancel{°\text{C}})$$

$$Q = -5.0 \times 10^4\ \text{J}$$

Statement: The copper pot releases 5.0×10^4 J of thermal energy as it cools to 21.0 °C.

LEARNING TIP

Mass Must Be in Kilograms When Using the Quantity of Heat Equation
Since the units for specific heat capacity are joules per kilogram degree Celsius, mass must be expressed in kilograms when using the quantity of heat equation.

Sample Problem 3

A block of iron starts off at a temperature of 22.0 °C. It is heated to 100.0 °C by placing it in boiling water. The quantity of thermal energy required for this temperature change to occur is 4.91×10^5 J. Calculate the mass of the iron block.

From Table 1 on page 281, we can determine that the specific heat capacity of iron is 4.5×10^2 J/(kg•°C). As in Sample Problems 1 and 2, we need to find the change in temperature before we can calculate the mass of the iron block using the quantity of heat equation.

Given: $T_1 = 22.0$ °C; $T_2 = 100.0$ °C; $c = 4.5 \times 10^2$ J/(kg•°C), $Q = 4.91 \times 10^5$ J

Required: m, mass of iron

Analysis: $\Delta T = T_2 - T_1$; $Q = mc\Delta T$

Solution:

$$\begin{aligned}\Delta T &= T_2 - T_1 \\ &= 100.0\ °\text{C} - 22.0\ °\text{C} \\ \Delta T &= 78.0\ °\text{C}\end{aligned}$$

Rearrange the quantity of heat equation to solve for mass.

$$Q = mc\Delta T$$

$$m = \frac{Q}{c\Delta T}$$

$$m = \frac{4.91 \times 10^5\ \cancel{\text{J}}}{\left(4.5 \times 10^2\ \frac{\cancel{\text{J}}}{\text{kg}\cdot\cancel{°\text{C}}}\right)(78.0\ \cancel{°\text{C}})}$$

$$m = 14\ \text{kg}$$

Statement: The iron block has a mass of 14 kg.

Practice

1. How much thermal energy is required to raise the temperature of 2.0 kg of water by 10.0 °C? T/I [ans: 8.4×10^4 J]
2. A glass window with a mass of 20.0 kg is heated to a temperature of 32.0 °C by the Sun. How much thermal energy is released by the window to the surroundings as it cools to 5.0 °C at night? T/I [ans: 4.5×10^5 J]
3. An aluminum block absorbs 1.0×10^4 J of energy from the Sun when its temperature increases by 5.0 °C. What is the mass of the block? T/I [ans: 2.2 kg]

The Principle of Thermal Energy Exchange

The **principle of thermal energy exchange** states that when a warmer object comes in contact with a colder object, thermal energy is transferred from the warmer object to the colder object until all of the thermal energy is evenly distributed in both objects. In other words, the object with the higher temperature transfers thermal energy to the object with the lower temperature until both objects have the same temperature. If you use the quantity of heat equation to calculate the thermal energy released by the warmer object (Q_{released}) and the thermal energy absorbed by the colder object (Q_{absorbed}), the two values are equal in magnitude but opposite in sign. Q_{released} is negative since ΔT is negative, and Q_{absorbed} is positive since ΔT is positive. Considering the law of conservation of energy, this makes sense. Thermal energy, like all other forms of energy, cannot be destroyed; it can only be transferred or transformed. In this case, the thermal energy is transferred from a warmer object to a colder object.

principle of thermal energy exchange when thermal energy is transferred from a warmer object to a colder object, the amount of thermal energy released by the warmer object is equal to the amount of thermal energy absorbed by the colder object

This conclusion assumes that the thermal energy remains in the two objects being studied and is not released to the surroundings. In most circumstances, however, some thermal energy will be released to the surrounding air, container, or surfaces.

Mathematically, $Q_{released}$ and $Q_{absorbed}$ should add to zero, since they represent equal amounts, but have opposite signs:

$$Q_{released} + Q_{absorbed} = 0$$

The following Tutorial demonstrates how the quantity of heat equation and the principle of thermal energy exchange may be used to calculate the specific heat capacities, masses, or temperatures of various objects.

Tutorial 2 Using the Principle of Thermal Energy Exchange to Determine Mass, Temperature, and Specific Heat Capacity

By mathematically combining the quantity of heat equation, $Q = mc\Delta T$, with the principle of thermal energy exchange, $Q_{released} + Q_{absorbed} = 0$, we can calculate the specific heat capacity, mass, or temperature of an object.

Sample Problem 1

A 60.0 g sample of metal is heated to 100.0 °C before being placed in 200.0 mL of water with an initial temperature of 10.0 °C. The metal–water combination reaches a final temperature of 15.6 °C. Determine the identity of the metal.

In this situation, the metal releases thermal energy and the water absorbs thermal energy. Use the data given to calculate the specific heat capacity of the metal, and then use the specific heat capacity and **Table 1** on page 281 to identify the metal.

Given: We will use the subscripts "m" for metal and "w" for water and let V_w represent the volume of the water.

metal: $m_m = 60.0\text{ g} = 0.0600\text{ kg}$; $T_{1m} = 100.0\text{ °C}$; $T_{2m} = 15.6\text{ °C}$

water: $V_w = 200.0\text{ mL}$; $T_{1w} = 10.0\text{ °C}$; $T_{2w} = 15.6\text{ °C}$; $c_w = 4.18 \times 10^3\text{ J/(kg}\cdot\text{°C)}$

Required: c_m, specific heat capacity of the metal

Analysis: $Q_{released} + Q_{absorbed} = 0$; $Q = mc\Delta T$

Solution: Since the quantity of heat equation is based on the mass of a substance, we must first calculate the mass of water, m_w, in kilograms, using the volume of water, V_w, provided and the density of water.

$$m_w = 200.0\text{ }\cancel{\text{mL}} \times \frac{1\text{ }\cancel{\text{g}}}{1\text{ }\cancel{\text{mL}}} \times \frac{1\text{ kg}}{1000\text{ }\cancel{\text{g}}}$$

$$= 0.2000\text{ kg}$$

The specific heat capacity of the metal, c_m, can be calculated by mathematically combining the quantity of heat equation, $Q = mc\Delta T$, and the principle of thermal energy exchange equation, $Q_{released} + Q_{absorbed} = 0$. We do this by substituting $Q = mc\Delta T$ for the metal and the water into $Q_{released} + Q_{absorbed} = 0$, remembering that the metal loses thermal energy and the water gains thermal energy.

$$m_m c_m \Delta T_m + m_w c_w \Delta T_w = 0$$

$$(0.0600 \text{ kg})(c_m)(15.6\ °C - 100\ °C) + (0.2000 \text{ kg})\left(4.18 \times 10^3 \frac{J}{kg \cdot °C}\right)(15.6\ °C - 10.0\ °C) = 0$$

$$(0.0600 \text{ kg})(c_m)(-84.4\ °C) + (0.2000 \cancel{\text{kg}})\left(4.18 \times 10^3 \frac{J}{\cancel{kg} \cdot \cancel{°C}}\right)(5.6\ \cancel{°C}) = 0$$

$$(-5.064 \text{ kg} \cdot °C)(c_m) + 4681.6 \text{ J} = 0 \text{ (two extra digits carried)}$$

$$(-5.064 \text{ kg} \cdot °C)(c_m) = -4681.6 \text{ J}$$

$$c_m = \frac{-4681.6 \text{ J}}{-5.064 \text{ kg} \cdot °C}$$

$$c_m = 9.24 \times 10^2 \text{ J/(kg} \cdot °C)$$

Statement: The specific heat capacity of the metal is 9.24×10^2 J/(kg • °C), so the metal is aluminum.

Sample Problem 2

A sample of iron is heated to 80.0 °C and placed in 100.0 mL of water at 20.0 °C. The final temperature of the mixture is 22.0 °C. What is the mass of the iron?

In this problem, you first find the heat capacities of the substances in Table 1. Then decide which substance absorbed and which released thermal energy. Then use the combined quantity of heat/principle of thermal energy exchange equation to calculate the mass of the iron.

Given: iron: $T_{1i} = 80.0$ °C; $T_{2i} = 22$ °C; $c_i = 4.5 \times 10^2$ J/(kg • °C)

water: $m_w = 100.0$ mL $= 100.0$ g $= 0.1000$ kg; $T_{1w} = 20.0$ °C; $T_{2w} = 22$ °C;
$c_w = 4.18 \times 10^3$ J/(kg • °C)

Required: m_i, mass of the iron

Analysis: $Q_{released} + Q_{absorbed} = 0$; $Q = mc\Delta T$

Solution: $Q_{released} + Q_{absorbed} = 0$

$$m_i c_i \Delta T_i + m_w c_w \Delta T_w = 0$$

$$(m_i)\left(4.5 \times 10^2 \frac{J}{kg \cdot °C}\right)(22.0\ °C - 80.0\ °C) + (0.1000 \text{ kg})\left(4.18 \times 10^3 \frac{J}{kg \cdot °C}\right)(22.0\ °C - 20.0\ °C) = 0$$

$$(m_i)\left(4.5 \times 10^2 \frac{J}{kg \cdot \cancel{°C}}\right)(-58.0\ \cancel{°C}) + (0.1000 \cancel{\text{kg}})\left(4.18 \times 10^3 \frac{J}{\cancel{kg} \cdot \cancel{°C}}\right)(2\ \cancel{°C}) = 0$$

$$(m_i)\left(-2.61 \times 10^4 \frac{J}{kg}\right) + 8.36 \times 10^2 \text{ J} = 0$$

$$(m_i)\left(-2.61 \times 10^4 \frac{J}{kg}\right) = -8.36 \times 10^2 \text{ J}$$

$$m_i = \frac{-8.36 \times 10^2 \cancel{J}}{\left(-2.61 \times 10^4 \frac{\cancel{J}}{kg}\right)}$$

$$m_i = 3.2 \times 10^{-2} \text{ kg}$$

Statement: The mass of the iron is 3.2×10^{-2} kg.

Sample Problem 3

During an investigation, 200.0 g of silver is heated to 90.0 °C. The hot silver is then placed into 300.0 g of ethyl alcohol that has an initial temperature of 5.0 °C. Determine the final temperature of the silver–alcohol mixture.

Given: silver: $m_s = 200.0\text{ g} = 0.2000\text{ kg}$; $T_{1s} = 90.0\text{ °C}$; $c_s = 2.4 \times 10^2\text{ J/(kg•°C)}$

ethyl alcohol: $m_a = 300.0\text{ g} = 0.3000\text{ kg}$; $T_{1a} = 5.0\text{ °C}$; $c_a = 2.46 \times 10^3\text{ J/(kg•°C)}$

Required: T_2, final temperature of the silver–ethyl alcohol mixture

Analysis: $Q_{released} + Q_{absorbed} = 0$; $Q = mc\Delta T$

Solution: $Q_{lost} + Q_{gained} = 0$

$$m_s c_s \Delta T_s + m_a c_a \Delta T_a = 0$$

$$(0.2000\text{ }\cancel{\text{kg}})\left(2.4 \times 10^2 \frac{\text{J}}{\cancel{\text{kg}}\cdot\text{°C}}\right)(T_2 - 90.0\text{ °C}) + (0.3000\text{ }\cancel{\text{kg}})\left(2.46 \times 10^3 \frac{\text{J}}{\cancel{\text{kg}}\cdot\text{°C}}\right)(T_2 - 5.0\text{ °C}) = 0$$

$$\left(48 \frac{\text{J}}{\text{°C}}\right)(T_2 - 90.0\text{ °C}) + \left(738 \frac{\text{J}}{\text{°C}}\right)(T_2 - 5.0\text{ °C}) = 0$$

$$\left(48 \frac{\text{J}}{\text{°C}}\right)T_2 - 4320\text{ J} + \left(738 \frac{\text{J}}{\text{°C}}\right)T_2 - 3690\text{ J} = 0$$

$$\left(786 \frac{\text{J}}{\text{°C}}\right)T_2 - 8010\text{ J} = 0$$

$$\left(786 \frac{\text{J}}{\text{°C}}\right)T_2 = 8010\text{ J}$$

$$T_2 = \frac{8010\text{ J}}{786 \frac{\text{J}}{\text{°C}}}$$

$$T_2 = 1.0 \times 10^1\text{ °C}$$

Statement: The final temperature of the ethyl silver–alcohol mixture is 1.0×10^1 °C.

Practice

1. Sun-Young places a 2.0 kg block of aluminum that had been heated to 100.0 °C in 1.5 kg of ethyl alcohol with an initial temperature of 18.0 °C. What is the final temperature of the mixture? T/I [ans: 45 °C]
2. A metal bar with a mass of 4.0 kg is placed in boiling water until its temperature stabilizes at 100.0 °C. The bar is then immersed in 500.0 mL of water with an initial temperature of 20.0 °C. The mixture reaches a temperature of 35.0 °C. What is the specific heat capacity of the metal bar? T/I [ans: 1.2×10^2 J/(kg·°C)]

Thermal Expansion and Contraction

thermal expansion the expansion of a substance as it warms up

As a substance absorbs thermal energy, some of this energy is transformed into kinetic energy. So the particles spread out and increase in volume. The increase in the volume of an object due to an increase in its temperature is called **thermal expansion**.

An understanding of thermal expansion is important to civil engineers, who design various types of structures. For example, metal-framed windows require rubber spacers to account for any changes in size caused by temperature changes. Bridges require special joints called expansion joints to prevent pressure from bending the metal components of the bridge on hot summer days (**Figure 1(a)**), and concrete sidewalks have spaces between the slabs to make room for expansion that occurs as temperatures rise (**Figure 1(b)**).

Likewise, when substances cool down, their particles release kinetic energy to the surroundings and the substance decreases in volume, resulting in **thermal contraction**. All substances that expand in warmer weather contract in colder weather. Civil engineers must keep these points in mind.

thermal contraction the contraction of a substance when it cools down

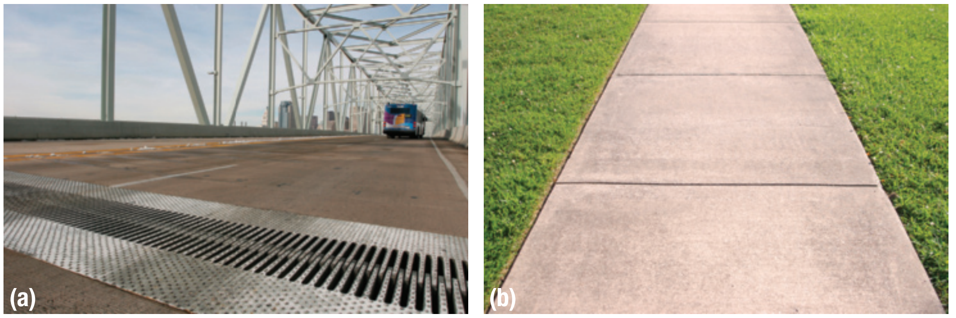

Figure 1 (a) Bridges have expansion joints to allow expansion during hot temperatures and contraction during cold temperatures. (b) Likewise, space must be left between concrete slabs to keep sidewalks from cracking when they expand in the heat and contract in the cold.

6.3 Summary

- Specific heat capacity is the amount of heat needed to raise the temperature of a 1 kg sample of a substance by 1 °C.
- The quantity of heat, or amount of thermal energy absorbed or released by an object, can be calculated using the equation $Q = mc\Delta T$.
- The principle of heat exchange states that thermal energy moves from a warm object to a cooler one until both objects reach a new constant temperature. This principle can be represented by the equation $Q_{released} + Q_{absorbed} = 0$.
- The absorption or release of thermal energy results in thermal expansion or contraction.

Investigation 6.3.1

Specific Heat Capacity of Brass (p. 304)

In this investigation, you will use the equations $Q = mc\Delta T$ and $Q_{released} + Q_{absorbed} = 0$ to calculate the specific heat capacity in a laboratory setting.

6.3 Questions

1. What is specific heat capacity? What does it tell you? K/U
2. Calculate the amount of thermal energy required to increase the temperature of 25.0 g of silver from 50.0 °C to 80.0 °C. K/U T/I
3. Calculate the amount of thermal energy released when 260.0 g of ice cools from −1.0 °C to −20.0 °C. K/U T/I
4. A 50.0 g sample of metal releases 1520 J of thermal energy when its temperature drops from 100.0 °C to 20.0 °C. What is the metal? K/U T/I
5. Calcium has a specific heat capacity of 6.3×10^2 J/(kg•°C). Determine the final temperature of a 60.0 g sample of calcium if it starts at 10.0 °C and absorbs 302 J of thermal energy. K/U T/I
6. A bar of pure gold is heated to 95.0 °C. The specific heat capacity of gold is 1.29×10^2 J/(kg•°C). The gold is placed into 500.0 mL of ethyl alcohol initially at a temperature of 25.0 °C. The final temperature of the mixture is 27.0 °C. What is the mass of the gold? K/U T/I
7. Danielle cools a 2.0 kg metal object to a temperature of −25.0 °C. She places the metal in 3.0 L of pure water initially at a temperature of 40.0 °C. The final temperature of the mixture is 36.0 °C. What is the specific heat capacity of the metal? K/U T/I
8. A 1.50×10^2 g piece of brass (specific heat capacity 3.80×10^2 J/(kg•°C)) is submerged in 400.0 mL of water at 27.7 °C. What is the original temperature of the brass if the mixture has a temperature of 28.0 °C? K/U T/I
9. Explain why temperature changes are important for civil engineers to consider when designing and evaluating building structures. K/U A
10. Research more about thermal expansion and contraction and how it is dealt with in the design of homes, schools, or other structures. Choose one innovation related to this topic and write a brief report. T/I C

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