13.2

1 FOCUS

Objectives

13.2.1 Identify factors that determine physical properties of a liquid.

13.2.2 Define evaporation in terms of kinetic energy.

13.2.3 Describe the equilibrium between a liquid and its vapor.

13.2.4 Identify the conditions at which boiling occurs.

Guide for Reading

Build Vocabulary L2

Concept Map After students read *Vapor Pressure*, have them make a concept map using the terms *evaporation, condensation, dynamic equilibrium,* and *vapor pressure*.

Reading Strategy L2

Compare and Contrast Have students write a short paragraph comparing and contrasting evaporation and boiling.

2 INSTRUCT

Connecting to Your World

Have students read the introduction and study the photograph of a lava flow. Ask, **Is lava a liquid or a solid?** *(a liquid)*

A Model for Liquids

Use Visuals L1

Figure 13.5 After students study the figure ask, **How are the colored water and the bromine vapor similar?** *(They can both flow and take the shape of their beakers.)* **How are water and bromine vapor different?** *(Water has a definite volume. The vapor doesn't have a definite volume.)* **According to kinetic theory, why doesn't the water spontaneously flow out of the beaker?** *(Attractions among water molecules hold the molecules together.)*

13.2 The Nature of Liquids

Guide for Reading

Key Concepts

- What factors determine the physical properties of a liquid?
- What is the relationship between evaporation and kinetic energy?
- When can a dynamic equilibrium exist between a liquid and its vapor?
- Under what conditions does boiling occur?

Vocabulary

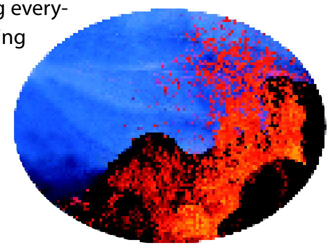
vaporization
evaporation
vapor pressure
boiling point
normal boiling point

Reading Strategy

Using Prior Knowledge Before you read, write a definition for the term *boiling point*. After you read this section, compare and contrast the definition of *boiling point* in the text with your original definition.

Connecting to Your World

The Kilauea volcano in Hawaii is the most active volcano in the world. It has been erupting for centuries. The hot lava oozes and flows, scorching everything in its path, occasionally overrunning nearby houses. When the lava cools, it solidifies into rock. The properties of liquids are related to intermolecular interactions. In this section you will learn about some of the properties of liquids.



A Model for Liquids

According to the kinetic theory, both the particles in gases and the particles in liquids have kinetic energy. This energy allows the particles in gases and liquids to flow past one another, as shown in Figure 13.5. Substances that can flow are referred to as fluids. The ability of gases and liquids to flow allows them to conform to the shape of their containers.

There is a key difference between gases and liquids. According to the kinetic theory, there are no attractions between the particles in a gas. But the particles in a liquid are attracted to each other. These intermolecular attractions keep the particles in a liquid close together, which is why liquids have a definite volume. **The interplay between the disruptive motions of particles in a liquid and the attractions among the particles determines the physical properties of liquids.**

Intermolecular attractions also reduce the amount of space between the particles in a liquid. Thus liquids are much more dense than gases. Increasing the pressure on a liquid has hardly any effect on its volume. The same is true of solids. For that reason, liquids and solids are known as condensed states of matter.

Figure 13.5 Both liquids and gases can flow. The liquid on the left is colored water. The gas on the right is bromine vapor. If a gas is denser than air, it can be poured from one container into another. These pictures were taken in a fume hood because bromine is both toxic and corrosive. **Predicting** ***Over time, what will happen to the gas in the uncovered beaker? Explain.***

Section Resources

Print

- **Guided Reading and Study Workbook,** Section 13.2
- **Core Teaching Resources,** Section 13.2 Review
- **Transparencies,** T142–T144
- **Small-Scale Chemistry Laboratory Manual,** Lab 20

Technology

- **Interactive Textbook with ChemASAP,** Animation 15, 16; Assessment 13.2

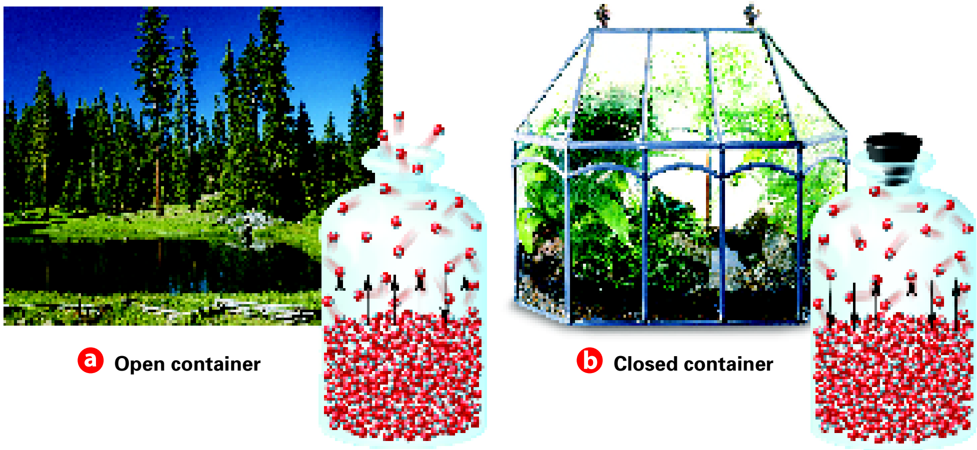


Figure 13.6 The process of evaporation has a different outcome in an open system, such as a lake, and a closed system, such as a terrarium. (a) In an open container, molecules that evaporate escape from the container. (b) In a closed container, the molecules cannot escape. They collect as a vapor above the liquid. Some molecules condense back into a liquid.

Evaporation

As you probably know from experience, water in an open container like the one in Figure 13.6a eventually moves into the air. The conversion of a liquid to a gas or vapor is called **vaporization.** When such a conversion occurs at the surface of a liquid that is not boiling, the process is called **evaporation.** Most of the molecules in a liquid don't have enough kinetic energy to overcome the attractive forces and escape into the gaseous state. **During evaporation, only those molecules with a certain minimum kinetic energy can escape from the surface of the liquid.** Even some of the particles that do escape collide with molecules in the air and rebound into the liquid.

You may have noticed that a liquid evaporates faster when heated. This occurs because heating the liquid increases the average kinetic energy of its particles. The added energy enables more particles to overcome the attractive forces keeping them in the liquid state. As evaporation occurs, the particles with the highest kinetic energy tend to escape first. The particles left in the liquid have a lower average kinetic energy than the particles that have escaped. The process is similar to removing the fastest runner from a race. The remaining runners have a lower average speed. As evaporation takes place, the liquid's temperature decreases. Therefore, evaporation is a cooling process.

You have observed the effects of evaporative cooling on hot days. When you perspire, water molecules in your perspiration absorb heat from your body and evaporate from your skin's surface. This evaporation leaves the remaining perspiration cooler. The perspiration that remains cools you further by absorbing more body heat.

Checkpoint ***What happens to the rate of evaporation when a liquid is heated?***

Interactive Textbook

Animation 15
Observe the phenomenon of evaporation from a molecular perspective.
with ChemASAP

Evaporation

Discuss L2

Use the photographs and drawings in Figure 13.6 to compare the evaporation of water in open and closed systems. Make sure students understand the difference between an open and closed system. In the open system, some of the molecules that evaporate from the surface collide with particles in the air and return to the liquid. But because the system is open, all the water molecules will eventually evaporate. In the closed system, the vapor accumulates above the liquid. The amount of vapor will increase until the rates of evaporation and condensation are equal.

Answers to...

Figure 13.5 It will disperse in the surrounding air.

Checkpoint It increases.

Vapor Pressure

TEACHER Demo

Vapor Pressure L2

Purpose Students will observe how the vapor pressure of a liquid changes with temperature.

Materials manometer, 1-L flask with 2-hole stopper, separatory funnel, short piece of glass tubing bent at a 90° angle, rubber hose, 50 mL acetone, ice water

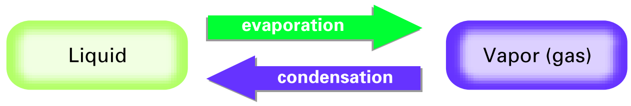
Safety To insert the glass tubing in the stopper, use glycerol. Wear gloves or hold the tubing in a towel to protect your hands. Be sure there are no open flames in the room because acetone is flammable.

Procedure You will need to obtain or construct a manometer and assemble the following apparatus. Insert a two-hole stopper into a 1-L flask. Into one hole of the stopper, insert a separatory funnel capable of containing 50 mL of acetone. Insert the bent glass tubing into the other hole. Use a rubber hose to connect the glass tubing to one end of the manometer. Be sure the hose fits both connections tightly. Use the manometer to measure the initial pressure. Then open the valve on the separatory funnel, and let the acetone drain into the flask. Have students observe the pressure in the flask. The maximum pressure observed is the vapor pressure of acetone at room temperature. Next, place the flask in ice water, and have students observe the change in pressure.

Expected Outcomes The pressure rises immediately as the acetone flows into the flask. The pressure falls when the flask is cooled.

Vapor Pressure

The evaporation of a liquid in a closed container differs from evaporation in an open container. No particles can escape into the outside air from the closed container in Figure 13.6b. When a partially filled container of liquid is sealed, some of the particles at the surface of the liquid vaporize. These particles collide with the walls of the sealed container and produce a vapor pressure. **Vapor pressure** is a measure of the force exerted by a gas above a liquid. Over time, the number of particles entering the vapor increases and some of the particles condense and return to the liquid state. The following equation summarizes the process.



Eventually, the number of particles condensing will equal the number of particles vaporizing. The vapor pressure will then remain constant. **In a system at constant vapor pressure, a dynamic equilibrium exists between the vapor and the liquid. The system is in equilibrium because the rate of evaporation of liquid equals the rate of condensation of vapor.**

At equilibrium, the particles in the system continue to evaporate and condense, but there is no net change in the number of particles in the liquid or vapor. The sealed terrarium in Figure 13.6b is an example of a closed container at equilibrium. The moisture on the inner walls of the terrarium is a sign that equilibrium has been established. Particles that once evaporated are condensing, but other particles are evaporating to take their place.

Vapor Pressure and Temperature Change An increase in the temperature of a contained liquid increases the vapor pressure. This happens because the particles in the warmed liquid have increased kinetic energy. As a result, more of the particles will have the minimum kinetic energy necessary to escape the surface of the liquid. The particles escape the liquid and collide with the walls of the container at a greater frequency. Table 13.1 gives the vapor pressures of some common liquids at various temperatures. The vapor pressure data indicates how volatile a given liquid is, or how easily it evaporates. Of the three liquids shown, diethyl ether is the most volatile and water is the least volatile.

Table 13.1
Vapor Pressure (in kPa) of Three Substances at Different Temperatures

	0°C	20°C	40°C	60°C	80°C	100°C
Water	0.61	2.33	7.37	19.92	47.34	101.33
Ethanol	1.63	5.85	18.04	47.02	108.34	225.75
Diethyl ether	24.70	58.96	122.80	230.65	399.11	647.87

Differentiated Instruction

Special Needs L1

If students are having difficulty grasping the concept of a dynamic equilibrium, try this analogy. There are three students on one side of a room and three students on the other side. One group has 30 foam balls. The other group has none. The balls represent water molecules. Students in the first group begin to toss the balls toward the other group. This action represents evaporation. At first the only process occurring is evaporation. But soon students in the second group begin to toss the balls back. This action represents condensation. When the number of balls being tossed in each direction at any given moment is equal, a dynamic equilibrium exists.

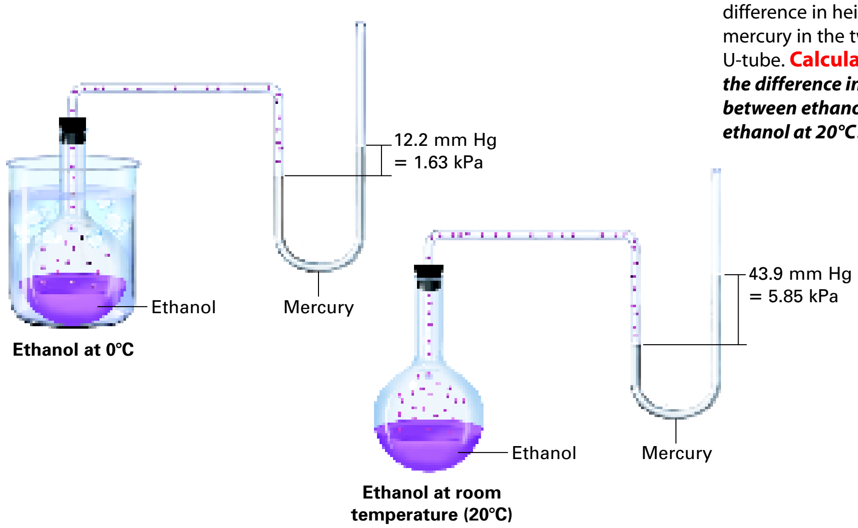
Vapor Pressure Measurements The vapor pressure of a liquid can be determined with a device called a manometer. Figure 13.7 shows how a simple manometer works. One end of a U-shaped glass tube containing mercury is attached to a container. The other end of the tube is open to the surrounding atmosphere. When there is only air in the container, the pressure is the same on both sides of the tube and the mercury level is the same in each arm of the tube. When a liquid is added to the container, the pressure in the container increases due to the vapor pressure of the liquid. The vapor pressure of the liquid pushes the mercury on the container side of the U-tube. The levels of mercury in the U-tube are no longer the same. You can determine the vapor pressure in mm of Hg by measuring the difference between the two levels of mercury. As the vapor pressure increases, so does the difference between the two levels.

Checkpoint ***What two physical changes occur in a partially filled, sealed container of liquid?***

Boiling Point

The rate of evaporation of a liquid from an open container increases as the liquid is heated. Heating allows a greater number of particles at the liquid's surface to overcome the attractive forces that keep them in the liquid state. The remaining particles in the liquid move faster and faster as they absorb the added energy. Thus, the average kinetic energy of the particles in the liquid increases and the temperature of the liquid increases. **When a liquid is heated to a temperature at which particles throughout the liquid have enough kinetic energy to vaporize, the liquid begins to boil.** Bubbles of vapor form throughout the liquid, rise to the surface, and escape into the air. The temperature at which the vapor pressure of the liquid is just equal to the external pressure on the liquid is the **boiling point** (bp).

Figure 13.7 The vapor pressure of a contained liquid can be measured in a manometer. The vapor pressure is equal to the difference in height of the mercury in the two arms of the U-tube. **Calculating** ***What is the difference in vapor pressure between ethanol at 0°C and ethanol at 20°C?***



CLASS Activity

Water versus Alcohol L2

Purpose Students will infer the relative vapor pressures of two liquids.

Materials 2 cotton balls, water, rubbing alcohol

Procedure Use cotton balls to simultaneously dab spots of water and rubbing alcohol onto the chalkboard. Have the class observe what happens to the spots. Ask students to infer which liquid has the greater vapor pressure at room temperature and explain their reasoning.

Boiling Point

Discuss L2

Explain that boiling is different from evaporation because evaporation can occur at any temperature. Boiling takes place at specific temperatures and pressures. Atmospheric pressure opposes the formation of bubbles in a liquid. Bubbles form only when the vapor pressure inside a bubble is equal to atmospheric pressure.

Answers to...

Figure 13.7 4.22 kPa or 31.7 mm Hg

Checkpoint evaporation of the liquid and condensation of the vapor

Section 13.2 (continued)

CLASS Activity

Temperature and Boiling L1

Purpose To dispel the misconception that the temperature of a liquid increases as it boils

Materials thermometer, beaker, ring stand, thermometer, clamp, water, hot plate

Safety Students must wear safety goggles, an apron, and mitts to protect them from the boiling water and steam. **CAUTION** *Steam can cause a more severe burn than boiling water can.*

Procedure Have students measure the temperature every 30 seconds for several minutes as water is heated and then boiled. Have students use their data to construct a graph of temperature versus time. Ask students to write a short paragraph explaining their results.

Relate L2

Discuss the effect of altitude on cooking time. Ask, **Why does it take longer to cook food in water at high altitudes?** *(Because atmospheric pressure decreases with altitude, water boils at a lower temperature and the food doesn't cook as quickly.)* **Why does food take less time to cook in a pressure cooker?** *(In a pressure cooker the pressure can be greater than atmospheric pressure. Thus, the boiling point of water can be higher, and the food takes less time to cook.)*

Interpreting Graphs L2

a. 60°C **b.** about 20 kPa **c.** about 30 kPa

Enrichment Question L3

Ask students to construct a similar graph for diethyl ether using the data in Table 13.1. Have them use the graph to determine the normal boiling point of diethyl ether. *(34.5°C)*

Sea Level Atmospheric pressure at the surface of water at 70°C is greater than its vapor pressure. Bubbles of vapor cannot form in the water, and it does not boil.

Sea Level At the boiling point, the vapor pressure is equal to atmospheric pressure. Bubbles of vapor form in the water, and it boils.

Atop Mount Everest At higher altitudes, the atmospheric pressure is lower than it is at sea level. Thus the water boils at a lower temperature.

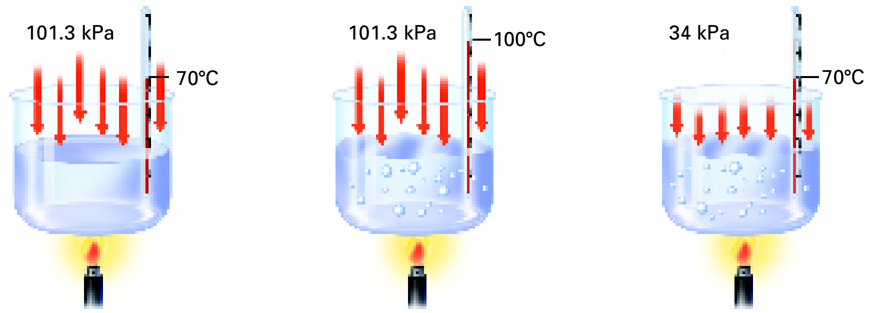
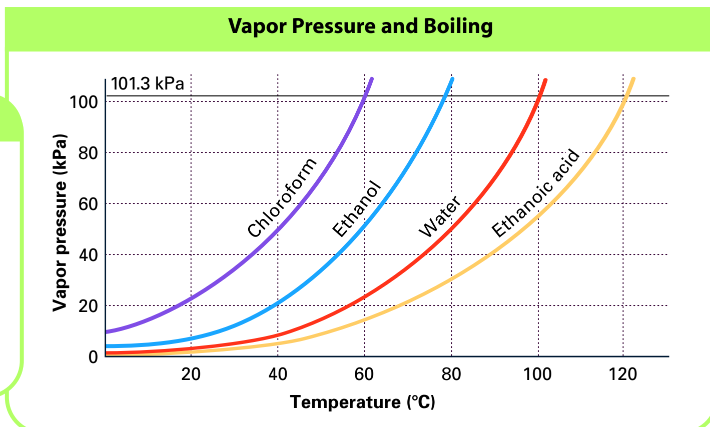


Figure 13.8 A liquid boils when the vapor pressure of particles within the liquid equals the atmospheric pressure. The boiling point varies with altitude.

Boiling Point and Pressure Changes Because a liquid boils when its vapor pressure is equal to the external pressure, liquids don't always boil at the same temperature. Figure 13.8 shows how a change in altitude affects the boiling point of water. Because atmospheric pressure is lower at higher altitudes, boiling points decrease at higher altitudes. In Denver, which is 1600 m above sea level, the average atmospheric pressure is 85.3 kPa. So water boils at about 95°C. In a pressure cooker, the vapor cannot escape and the vapor pressure increases. So water boils at a temperature above 100°C and food can cook more quickly.

Look at the vapor pressure versus temperature graph in Figure 13.9. You can use the graph to show how the boiling point of a liquid is related to vapor pressure. At a lower external pressure, the boiling point decreases. The particles in the liquid need less kinetic energy to escape from the liquid. At a higher external pressure, the boiling point increases. The particles in the liquid need more kinetic energy to escape from the liquid.

Figure 13.9 On the graph, the intersection of a curve with the 101.3-kPa line indicates the boiling point of that substance at standard pressure.



INTERPRETING GRAPHS

a. Analyzing Data What is the boiling point of chloroform at 101.3 kPa?
b. Analyzing Data What is the vapor pressure of ethanol at 40°C?
c. Analyzing Data What would atmospheric pressure need to be for ethanoic acid to boil at 80°C?

Differentiated Instruction

Gifted and Talented L3

Ask students to use the data in Table 13.1 to construct a graph of vapor pressure versus temperature. They will need to plot log P versus $1/T$, where P is the vapor pressure in mm Hg and T is the absolute temperature.

Table 13.2

The Normal Boiling Points of Several Substances

Name and formula	Boiling Point (°C)
Carbon disulfide (CS_2)	46.0
Chloroform ($CHCl_3$)	61.7
Methanol (CH_4O)	64.7
Tetrachloromethane (CCl_4)	76.8
Ethanol (C_2H_6O)	78.5
Water (H_2O)	100.0

Boiling is a cooling process similar to evaporation. During boiling, the particles with the highest kinetic energy escape first when the liquid is at the boiling point. Turning off the source of external heat drops the liquid's temperature below its boiling point. Supplying more heat allows more particles to acquire enough kinetic energy to escape. However, the temperature of the boiling liquid never rises above its boiling point. If heat is supplied at a greater rate, the liquid only boils faster. The vapor produced is at the same temperature as that of the boiling liquid. Although the vapor has the same average kinetic energy as the liquid, its potential (or stored energy) is much higher. Thus, a burn from steam is more severe than one from an equal mass of boiling water at the same temperature.

Interactive Textbook
Animation 16 Relate vapor pressure and boiling point to intermolecular attractive forces.
with ChemASAP

Normal Boiling Point Because a liquid can have various boiling points depending on pressure, the **normal boiling point** is defined as the boiling point of a liquid at a pressure of 101.3 kPa. For example, the normal boiling point of water is 100°C. Table 13.2 lists the normal boiling points of six molecular compounds.

13.2 Section Assessment

8. **Key Concept** What factors help determine the physical properties of liquids?
9. **Key Concept** In terms of kinetic energy, explain how a molecule in a liquid evaporates.
10. **Key Concept** A liquid is in a closed container and has a constant vapor pressure. What is the relationship between the rate of evaporation of the liquid and the rate of condensation of the vapor in the container?
11. **Key Concept** What condition must exist for a liquid to boil?
12. Use Figure 13.9 to determine the boiling point of each liquid.
    a. ethanoic acid at 27 kPa
    b. chloroform at 80 kPa
    c. ethanol at 50 kPa
13. Explain why the boiling point of a liquid varies with atmospheric pressure.
14. Explain how evaporation lowers the temperature of a liquid.

Writing Activity

Contrast Paragraph Look for high-altitude cooking directions on packages of cake, brownie, or muffin mixes. Contrast them with standard directions.

Interactive Textbook
Assessment 13.2 Test yourself on the concepts in Section 13.2.
with ChemASAP

3 ASSESS

Evaluate Understanding L2

To summarize section content, ask, **What are some of the general characteristics that distinguish a liquid from a gas?** *(Gases can expand to fill their containers. Gases are easily compressed. Liquids conform to the shape of their containers, but do not expand to fill them. Liquids are not as easy to compress as gases because the spaces between particles in a liquid are much smaller than those in a gas.)*

Reteach L1

Remind students that the temperature at which the vapor pressure of a liquid is equal to the atmospheric pressure is the boiling point of the liquid. The exact temperature at which boiling occurs depends on the strength of the intermolecular attractions between molecules in the liquid and the magnitude of the atmospheric pressure. Explain that when the atmospheric pressure is reduced below the vapor pressure of water, water will boil at room temperature.

Writing Activity

Examples of recommended adjustments include adding more flour, greasing nonstick muffin tins, reducing the amount of leavening, increasing the amount of liquids, increasing the cooking time, and increasing the baking temperature.

Interactive Textbook

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 13.2.

with ChemASAP

Section 13.2 Assessment

8. the interplay between the disruptive motions of particles in a liquid and the attractions among the particles
9. A molecule with a certain minimum kinetic energy can escape from the surface of the liquid and vaporize.
10. Rate of evaporation of the liquid equals the rate of condensation of the vapor.
11. Particles throughout the liquid must have enough kinetic energy to vaporize.
12. **a.** about 76°C **b.** about 52°C **c.** about 62°C
13. Boiling occurs when the vapor pressure of a liquid equals the external pressure. If the atmospheric pressure changes, the boiling point will change.
14. When the molecules with the highest kinetic energy escape from the liquid, the average kinetic energy of the remaining particles is lower and the temperature decreases.