Topic 8.1

Internal Structure and Density

Learning Objectives

- Describe the general characteristics of fluids and relate them to the varying interactions between atoms and molecules.
- Characterize a fluid in terms of its density and viscosity.

Topic Questions

- What is a fluid?
- What are some properties that characterize a fluid, and how are they determined?
- What is an ideal fluid?

8.1.01 Properties of Fluids

[8.1.A.1 8.1.A.2 8.1.A.3 8.1.A.4]

A **fluid** is a substance that has no fixed shape and has the ability to flow, such as a liquid or a gas. These defining characteristics of fluids stem from the arrangement of their constituent atoms or molecules and distinguish them from **solid materials** (see Figure 8.1).

Atoms in solids are close together and held strongly in place by the forces between them. Consequently, solids have both a definite **volume** and a definite shape.

Atoms in liquids are also close together but the forces between them are weaker, so they have the ability to move and slide past each other. As a result, liquids have a definite volume but no definite shape. Liquids conform to the shape of their container without expanding or compressing.

In gases, atoms are spread far apart with very weak forces between them, resulting in no definite volume and no definite shape. Gases conform to both the shape and the volume of their container, easily expanding or compressing as necessary.

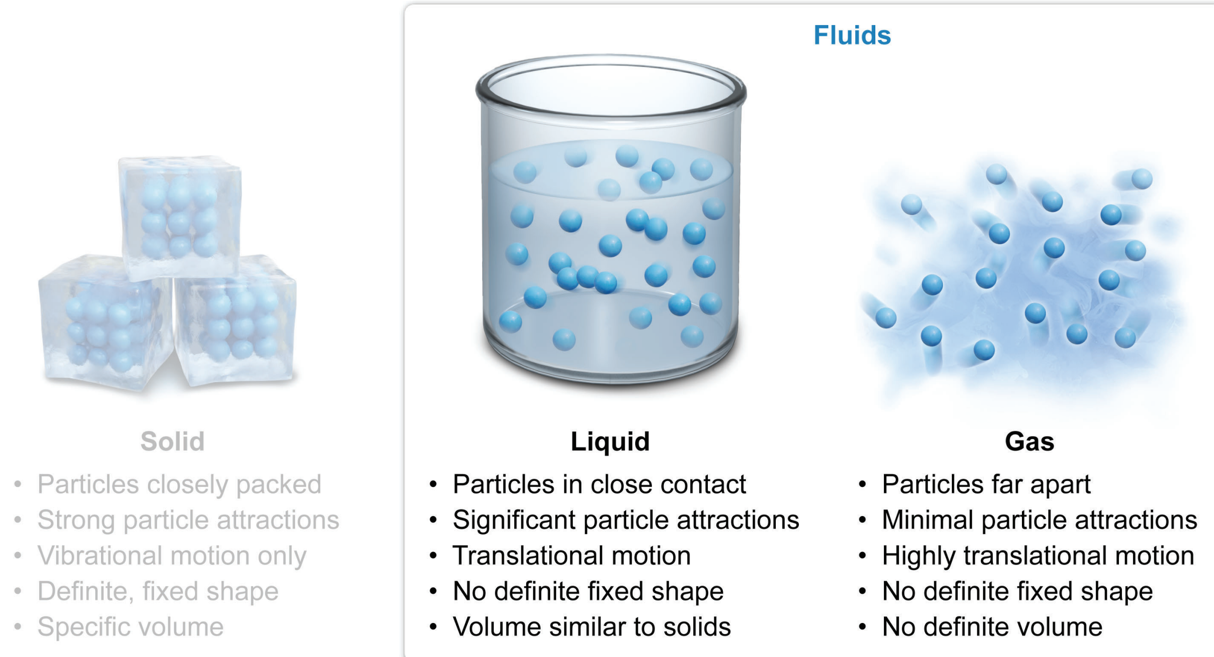

Figure 8.1 Differences between atomic arrangements in solids, liquids, and gases result in different characteristics.

Because fluids can flow, change shape, and divide into smaller portions, fluids are often described in terms of properties that do not depend on the amount of fluid present. One such property is the density of the fluid.

Density ρ is defined as the ratio of mass m per volume V of a substance:

$$\rho = \frac{m}{V}$$

Since the particles that make up liquids are already close together, liquids tend to maintain a relatively constant density even when subjected to compressive forces. In other words, liquids are nearly **incompressible** (Figure 8.2). Gases, however, consist of particles that are relatively far apart from each other, which makes them easily compressible with a density that can vary greatly.

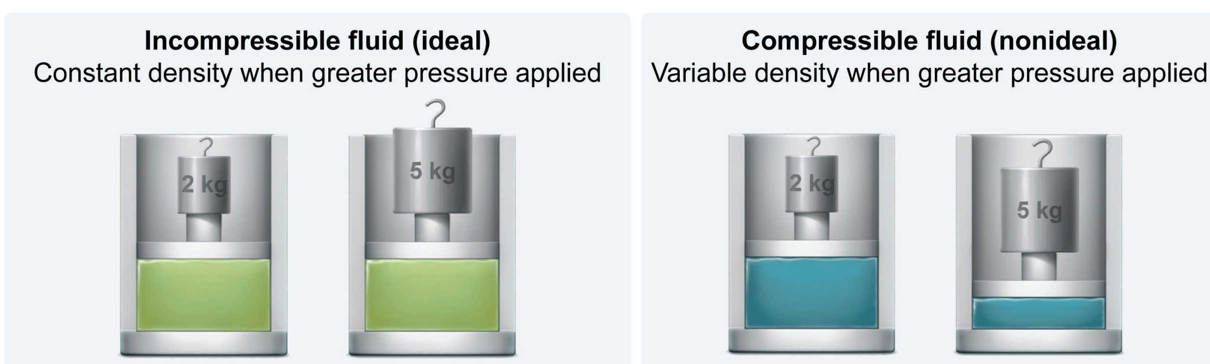

Figure 8.2 Incompressible vs. compressible fluids.

In addition to density, another property that characterizes a fluid is its **viscosity**. A fluid's viscosity is based on the amount of internal friction that exists between its particles and governs how easily it can flow. As shown in Figure 8.3, a high viscosity fluid (eg, honey) has more friction between its particles and does not flow as easily as a low viscosity fluid (eg, water).

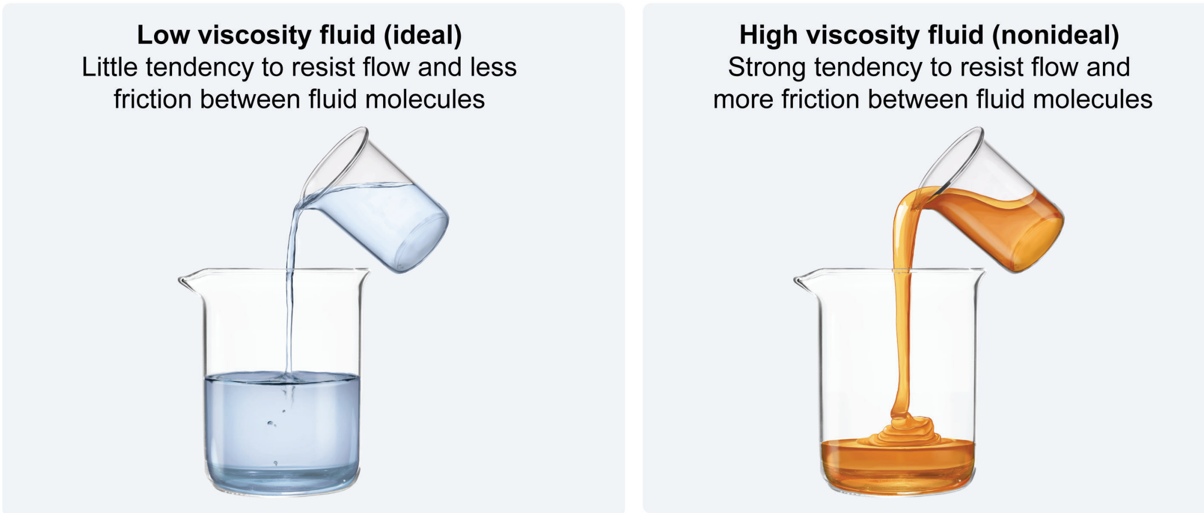

Figure 8.3 Low viscosity vs. high viscosity fluids.

A fluid that has zero (or negligible) viscosity and is also incompressible is said to be an ideal fluid. In other words, an ideal fluid is one with a constant density and negligible friction.

For example, consider a situation where an experimenter initially pours 57.3 g of an unknown (ideal) fluid into a graduated cylinder and measures the volume to be 62.5 mL If the experimenter in this situation only needs 45.0 g of the fluid, what volume of the fluid must be poured out?

To solve this problem, we begin by determining the density of the fluid based on the mass and volume of the initial sample:

$$\rho = \frac{m_1}{V_1} = \frac{57.3\ \mathrm{g}}{62.5\ \mathrm{mL}} = 0.917\,\frac{\mathrm{g}}{\mathrm{mL}}$$

Since the fluid is ideal, its density remains the same even if some of it is removed. This means that 45.0 g of the fluid will still have the same density as the larger sample, but it will have a new volume that can be calculated by rearranging the density formula:

$$\rho = \frac{m_2}{V_2}$$

$$V_2 = \frac{m_2}{\rho}$$

$$V_2 = \frac{45.0\ \mathrm{g}}{0.917\,\frac{\mathrm{g}}{\mathrm{mL}}} = 49.1\ \mathrm{mL}$$

To determine the volume of fluid that must be poured out, subtract the final volume of fluid from the initial volume:

$$V_{\mathrm{pour}} = V_2 - V_1 = 62.5\ \mathrm{mL} - 49.1\ \mathrm{mL} = 13.4\ \mathrm{mL}$$

A fluid that is commonly featured in exam questions is **water**, because its density is exactly equal to 1 g/cm^3. Since a cubic centimeter is equivalent to a milliliter, the density of water can also be expressed in units of g/mL:

$$\rho_{\mathrm{water}} = 1.0\,\frac{\mathrm{g}}{\mathrm{cm}^3} = 1.0\,\frac{\mathrm{g}}{\mathrm{mL}}$$

or, in standard SI units of kg/m^3:

$$\rho_{\mathrm{water}} = 1{,}000\,\frac{\mathrm{kg}}{\mathrm{m}^3}$$

For example, consider an open cylindrical container with a height of 12 cm, an inner radius of 3.5 cm, and 270 g of water inside, as shown in Figure 8.4. When olive oil, which has a density of 0.92 g/cm^3, is poured carefully on top of the water, it will form a separate layer above the water without mixing. How many grams of olive oil can be added to the container before it overflows?

Figure 8.4 Pouring olive oil into a container of water.

Starting with the known density and mass of the water, the volume of water V_w in the container can be calculated:

$$\rho_w = \frac{m_w}{V_w}$$

$$V_w = \frac{m_w}{\rho_w} = \frac{270\ \cancel{\text{g}}}{1\ \frac{\cancel{\text{g}}}{\text{cm}^3}} = 270\ \text{cm}^3$$

Notice that the volume of water in cm^3 has the same value as the mass of water in grams.

The height and radius of the cylindrical container can then be used to determine the volume of the container V_c by utilizing the formula for the volume of a cylinder:

$$V_c = \pi r^2 h = \pi(3.5\ \text{cm})^2(12\ \text{cm}) = 462\ \text{cm}^3$$

Taking the difference between the volume of the entire container and the volume of water that partially fills it yields the volume of olive oil necessary to fill the remaining space:

$$V_{oil} = V_c - V_w = 462\ \text{cm}^3 - 270\ \text{cm}^3 = 192\ \text{cm}^3$$

Finally, the mass of the olive oil m_{oil} to be added can be determined from the volume and density of the oil:

$$\rho_{\text{oil}} = \frac{m_{\text{oil}}}{V_{\text{oil}}}$$

$$m_{\text{oil}} = \rho_{\text{oil}} \cdot V_{\text{oil}} = \left(0.92\,\frac{\text{g}}{\cancel{\text{cm}^3}}\right)(192\,\cancel{\text{cm}^3}) = 177\text{ g}$$

Topic 8.1 Internal Structure and Density
Check for Understanding Quiz

1. Which of the following statements correctly describes the molecular arrangement of a substance and a property that necessarily results from that arrangement?

   A. Molecules are closely packed together, resulting in a substance with a definite shape.

   B. Molecules are spread far apart, resulting in a substance with a definite volume.

   C. Molecules are closely packed together, resulting in a substance that is incompressible.

   D. Molecules are free to easily slide past each other, resulting in a substance with a high viscosity.

2. Which of the following fluids would have the greatest density?

   A. Fluid A, which has a mass m and volume V

   B. Fluid B, which has a mass $2m$ and volume ½ V

   C. Fluid C, which has a mass ½ m and volume $2V$

   D. Fluid D, which has a mass $2m$ and volume $2V$

Note: Answers to this quiz are in the back of the book (appendix).