17.3 Buoyancy of Fluids

Have you ever noticed how easy it is to do a push-up to lift yourself up and out of a swimming pool? It’s much easier than doing push-ups on land. That’s because the water is exerting an upward force on you. In this section, you will learn more about the force that fluids exert on an object. By the end of the section, you should be able to define buoyancy and explain Archimedes’ principle. You should also be able to explain how gases exert forces when they are confined in a container.

What is buoyancy?

A simple experiment can be used to demonstrate the upward force of water you can feel in a swimming pool. A piece of string is tied to a rock, and its weight is measured with a spring scale. The rock weighs 2.25 newtons. Next, the rock is immersed in water, but not allowed to touch the bottom or sides of the container. Now the spring scale measures 1.8 newtons. The water has exerted a force of 0.45 newtons on the rock. We call this force buoyancy. Buoyancy is a measure of the upward pressure a fluid exerts on an object.

What is Archimedes’ principle?

In the third century BC, a Greek mathematician named Archimedes made an important discovery about the buoyant force. He realized that the force exerted on an object in a liquid is equal to the weight of the fluid displaced by the object. We call this relationship Archimedes’ principle.

Archimedes’ principle tells us that the water displaced by the rock in the experiment above had a weight of 0.45 newtons.

Do all fluids exert the same buoyant force on an object?

Archimedes’ principle can be used to find the buoyant force of liquids other than water. For example, we could immerse the rock from the previous experiment in glycerin, which has a density of 1.26 grams/cm³.

The rock will always displace the same volume of liquid, in this case, about 43 milliliters. Forty-three milliliters of glycerin weigh 0.53 newtons. Therefore, the glycerin exerts a buoyant force of 0.53 newtons on the rock.
Why objects sink and float

Buoyancy helps explain why some objects sink and others float. If the buoyant force is greater than its weight, the object floats. In the example above, we would need a buoyant force greater than 2.25 newtons to make our rock float.

If the buoyant force is less than its weight, then the object will sink. Neutral buoyancy occurs when the buoyant force is equal to the weight of the object. When an object is neutrally buoyant, it will stay immersed in the liquid at the level where it was placed. Scuba divers use weights and a buoyancy control device (BCD) to help them maintain neutral buoyancy. When a scuba diver is neutrally buoyant he or she can swim and move underwater without rising to the top or sinking.

Why does a block of steel sink, but a steel boat float?

Archimedes’ principle explains why a substance in one shape will float and in another shape will sink. A cubic meter of steel has a weight of 76,400 newtons. When placed in water, the block would displace one cubic meter of water. The water would have a weight of 9,800 newtons. The weight of the steel block is much greater than the weight of the displaced water. As expected, the block sinks.

Imagine the same block of steel flattened into a thin sheet, its sides bent up into the shape of a boat. That original block of steel, now shaped to be hollow inside, might occupy 10 cubic meters of space instead of one. Ten cubic meters of displaced water has a weight of 98,000 newtons. Now the displaced water weighs more than the steel, which still weighs 76,400 newtons.

When placed in the water, your steel boat would settle in the water until it reached a level where it displaced 76,400 newtons of water. Then the upward force exerted by the water would equal the downward force exerted by the boat.

You can try a similar experiment with a stick of clay and a bucket of water. Drop the stick of modeling clay into the bucket and observe what happens. Now mold the clay into a boat shape. Can you make a clay boat float?
Buoyancy and gases

Why do hot air balloons float?

Buoyancy is a property of gases as well as liquids. A helium balloon floats because it displaces a very large volume of air. This volume of air weighs more than the total weight of the balloon, the gondola (the basket that the balloon carries), and the people in the gondola. The hot-air balloon floats because it weighs less than the volume of air displaced.

The relationship between the temperature and volume of a gas

So how can you get a hot-air balloon to take up a lot of space? You probably know the answer to this question. “Hot air” is important. To get their balloons to take flight, balloonists use a torch to heat the air molecules inside the balloon. Heated molecules move with greater energy. As they collide with each other and the sides of the balloon, they take up more space. In effect, the air in the balloon expands. This illustrates an important relationship, known as Charles’ law, which was discovered by Jacques Charles in 1787. According to Charles’ law, the volume of a gas increases with increasing temperature. The volume of a gas shrinks with decreasing temperature.

Charles’ law

The volume of a gas increases with increasing temperature.
The volume of a gas decreases with decreasing temperature.

The buoyancy of hot air

Charles law helps explain why the air inside the balloon becomes much less dense than the air outside the balloon. Because it is less dense, a hot-air balloon will rise in the atmosphere until the density of the air displaced by the balloon matches the average density of the air inside the balloon and the matter of the balloon itself. Stated another way, the weight of the air displaced by the balloon provides buoyant force to keep the balloon in flight.
Gases and pressure

What is pressure? Have you ever pumped up a bicycle tire? What is happening inside of the tire? As you pump more air into the tire, more and more particles of air are pushed into the tire, increasing the pressure inside. On a microscopic level, each particle of air collides with the inside walls of the tire, exerting a force which pushes the inner surface of the tire outward. As you pump more air into the tire, there are more particles that can exert forces on the inside walls of the tire. The forces of all of the particles of air inside the tire add together to create pressure.

Units of pressure Pressure is the force acting on a unit area of surface. You may have noticed that tire pressure is usually measured in units of pound per square inch (psi). A typical bicycle tire should be inflated to about 60 psi. The SI unit for pressure is called a pascal (Pa). One pascal is equal to one newton of force acting on one square meter of surface area.

What is atmospheric pressure? The air you breathe is made of many different gases including carbon dioxide, oxygen, and nitrogen. The Earth’s air, known as the atmosphere, is held in place by the force of gravity on the air particles. Without the force of gravity, the air you breathe would escape into space. At the Earth’s surface, the atmosphere exerts a pressure of 101,300 pascals, or 101,300 newtons of force per square meter—about the weight of an elephant! Atmospheric pressure decreases with altitude. This is why the atmospheric pressure on top of a mountain is less than the atmospheric pressure at sea level. Does this explain why your ears pop when you fly in a plane?

How are pressure and volume related? Suppose you pump five liters of air into a beach ball. If you pump the same amount of air into a basketball half the size of the beach ball, which has a greater amount of pressure? Assuming that the temperature remains constant, the basketball has twice as much pressure as the beach ball. This is because if you squeeze the same amount of gas into a smaller container, the gas particles collide with the walls of the container more often, increasing the pressure. On the other hand, the gas particles inside of the beach ball occupy twice as much volume so they collide with the walls less often. This property of gases, called Boyle’s law, was discovered by Robert Boyle in 1662.
Boyle’s law

As the pressure of a gas increases, its volume decreases proportionately.
As the pressure of a gas decreases, its volume increases proportionately.

Boyle’s law equation

The relationship between pressure and volume for a gas, when temperature remains constant, is evident in the graph in figure 17.18. This relationship can also be expressed by the following equation:

\[ P_1 V_1 = P_2 V_2 \]

This equation shows that the product of the initial pressure and volume of a gas is equal to the product of the final pressure and volume of a gas when either pressure or volume is changed. The example below shows how to solve a problem using the equation.

Example problem

A kit used to fix flat tires consists of an aerosol can containing compressed air and a patch to seal the hole in the tire. Suppose 5 liters of air at atmospheric pressure (101.3 kilopascals) is compressed into a 0.5 liter aerosol can. What is the pressure of the compressed air in the can?

What do you know?

The equation for Boyle’s law is: \( P_1 V_1 = P_2 V_2 \)

\( P_1 = 101.3 \text{ kPa} \); \( V_1 = 5 \text{ L} \); \( P_2 = \text{unknown} \); \( V_2 = 0.5 \text{ L} \)

Rearrange the variables

I am solving for \( P_2 \) and the equation is: \( P_2 = \frac{P_1 \cdot V_1}{V_2} \)

Plug in the numbers

\( P_2 = \frac{101.3 \text{ kPa} \times 5.0 \text{ L}}{0.5 \text{ L}} \)

Solve the problem

The pressure inside the aerosol can is 1,013 kPa.

Atmospheric pressure

The pressure exerted by the Earth’s atmosphere at sea level is 101,300 pascals (Pa). Since pascals are very small, other units of pressure are often used. The pressure of the Earth’s atmosphere at sea level is also equal to:

- 101.3 kilopascals (kPa)
- 1.00 atmosphere (atm)
- 14.7 pounds per inch\(^2\) (psi)
- 760 millimeters of mercury (mm Hg)