Course Learning Outcomes for Unit VI

Upon completion of this unit, students should be able to:

6. Explain numerous phenomena using fluid mechanics laws.
   - 6.1 Utilize the relationship between mass, density, and volume.
   - 6.2 Apply the concept of Pascal's principle and Archimedes' principle.
   - 6.3 Recognize heat and energy with phase changes of matter.

Required Unit Resources

Chapter 11: Fluids

Chapter 12: Temperature and Heat

Unit Lesson

What Are Fluids?

Unlike solids, liquids and gasses do not have a definite shape unless they are kept in a container. Something is referred to as fluid when it can flow without specific configuration. Both liquids and gases are examples of fluids. Both water and air move from place to place if they are not confined in a vessel. Both of them show a similar pattern of motion, but their density is very different because it depends on the property of matter. Usually, gases have lower densities than liquids have because the average distance between molecules is greater in gases than in liquids. The density of gases is greatly dependent on pressure and temperature.

Mass = Density x Volume

Mass density is defined as the mass of an object divided by the volume of the object. The SI unit of mass is kg, that of density is kg / m^3, and that of volume is m^3.

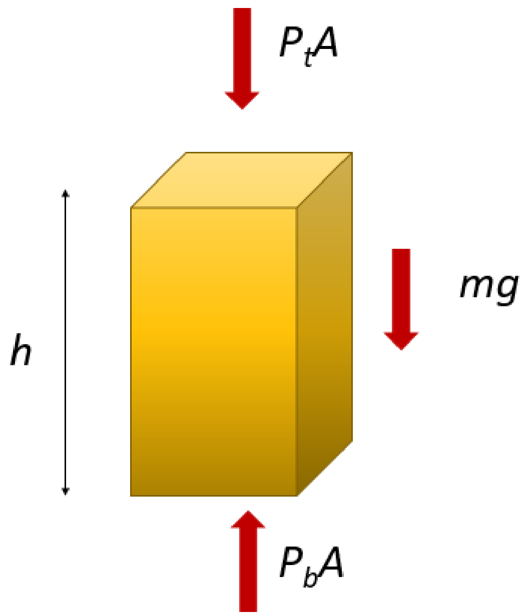
Sample Question 1: If the mass of a diamond box is 100 kg, what is the volume of the box?

Solution: Use the formula mass = density x volume. The density of diamond is 3520 kg/m^3 from Table 11.1 under Section 11.1 in Chapter 11 of the eTextbook (Cutnell et al., 2022). So, the volume is the mass divided by the density.

Pressure in Fluids

When a force (F) acts on area (A) in a fluid, the pressure (P) can be expressed as $P = F / A$. Here, we only consider the magnitude of F, so P is a scalar and its unit is N / m^2 = Pa (Pascal). Atmospheric pressure at sea level is about 101,300 Pa = 1 atm.

Force = Pressure x Area



You may experience greater pressure as you go deeper into a swimming pool or in an ocean. What is the relation between pressure and depth? Let's consider one column of water with height h below the figure in a large swimming pool. The area (A) of the top face is the same as that of the bottom face. The pressure (P_t) on the top face creates a downward force or P_tA. The pressure (P_b) creates an upward force or P_bA. Also, the weight (mg) due to gravity points downward.

Water is at rest, and thus its acceleration is zero. That is, the column is in equilibrium. We can apply Newton's second law, and the summation of the vertical forces is zero: $P_bA – P_tA$ – mg = 0. Use $m = \rho V = \rho Ah$. Then, $P_b = P_t + \rho gh$. You can clearly see that the pressure at a deeper level is greater than the pressure at a shallow level if the density is not changing or if it is incompressible. In the case of gas, the density varies according to the vertical distances or if it is compressible, so the formula only works when h is very small. For instance, the density of our atmosphere varies significantly from the Earth's surface to higher altitudes. The important thing is that the pressure difference between lower and higher levels comes from the height, or the vertical distance, not the horizontal distance within the fluid. See Figure 11.5 in Section 11.3 of Chapter 11 in the eTextbook (Cutnell et al., 2022).

Pascal's and Archimedes' Principles

Pascal's principle states that any externally applied pressure is transmitted undiminished to everywhere in a completely enclosed fluid at rest. This is the same analysis of the above equation: $P_b = P_t + \rho gh$. The bottom pressure is equal to the sum of top pressure, which is the externally applied pressure, and the static fluid pressure due to the weight of the fluid. For instance, this is the case with the mechanism of a hydraulic car lift when the static fluid pressure is zero. See Figure 11.15 in Section 11.5 of Chapter 11 in the eTextbook (Cutnell et al., 2022).

> **Sample Question 2:** A young lady is visiting a medical research center to measure her blood pressure difference between the blood pressure in the anterior tibial artery at the foot and the blood pressure in the aorta at the heart. Let's assume that the blood in her body is a static fluid, and the vertical distance between the feet and the heart is 1.1 meter. What is the blood pressure difference between them? The density of blood is 1060 kg/m^3.
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> **Solution:** Let P_b be the blood pressure in the anterior tibial artery at the foot, and P_t be the blood pressure in the aorta at the heart. According to Pascal's principle, $P_b = P_t + \rho gh$. Here, ρ(= 1060 kg/m^3) is the density of blood. The acceleration g(= 9.8 m/s^2) is due to gravity, and h is given as 1.1 m. So, the difference $P_b - P_t = \rho gh$ = 1060 x 9.8 x 1.1 = 11426.8 Pa.

You may experience that it is very hard to push a beach ball under the surface of the water. The water, in fact, pushes back, and this upward force is called the buoyant force, which arose because of the pressure of fluids depending on the depths. In the figure above, the net upward force is called the buoyant force $F = P_bA - P_tA = \rho ghA$ = mg = weight. Notice that the buoyant force does not depend on the shape of the object. Archimedes discovered this property more than 2,000 years ago. Archimedes' principle states that a fluid exerts a buoyant force to an immersed object. The magnitude of the buoyant force equals the weight of the displaced fluid.

> **Magnitude of Buoyant Force = Weight of Displaced Fluid**

Bernoulli's Equation and Its Application

When fluids are in motion, they move with a variety of options. You may have observed that water flows calmly in a shallow stream and violently in a steep valley. The air blows very gently sometimes and vigorously with great speed at other times. In order to characterize the type of fluids, compressible/incompressible and viscous/nonviscous categories are used. When the density of a fluid is almost constant, the fluid is said to be incompressible. Luckily, most liquids are incompressible, but all gases are not.

When fluid like honey does not flow easily, it is a viscous fluid. On the other hand, water flows very easily because its viscosity is low. Incompressible and nonviscous fluids are called ideal fluids; this is great to describe the motion of fluids with mathematical equations. For steady flow, Bernoulli studied the behavior of ideal fluids. Its result is in his equation: $P + 1/2\ \rho v^2 + \rho gy$ = constant. In this equation, y is the elevation at any point, and v is the fluid speed. If the flow speed is not changing, the above equation goes back to the pressure equation when water is at rest. If the flow is horizontal, that is, there is no elevation between two points, the pressure is related to the speed. The higher fluid pressure makes the slow-moving flow and vice versa. In addition, when the volume flow rate Av = constant, if the cross-sectional area of a tube is large, the fluid speed is small and vice versa.

With these fluid equations, we can describe the motion of liquids in a plumbing system, the speed changes of oil in a pipe, and even the dynamics of an airplane wing.

Three Temperature Scales

A thermometer is used to measure temperature. We can make a thermometer due to the fact that most materials expand when the heat is added. For example, a mercury thermometer, which consists of a mercuryfilled glass bulb connected to a capillary tube, is widely used. When mercury is heated, the expanded amount of mercury is directly proportional to the increased temperature.

Two common temperature scales are the Fahrenheit and Celsius scales. Both scales are based on boiling and freezing points of water at atmospheric pressure. In the case of the Celsius scale, the boiling point is 100°C, and the freezing point is 0°C. For the Fahrenheit scale, the boiling point is 212° F, and the freezing point is 32°F. The distance between these two points are divided equally to indicate the temperature scales. The separation between the freezing and boiling points on the Celsius scale is 100 degrees while that on the Fahrenheit scale is 180 degrees. The converting formula for the two scales is °F = 1.8°C + 32.

Sample Question 3: The normal human body temperature is 98.6°F, which was determined in the 19th century. A more recent study announced that it is 98.2°F. Express the difference in the temperature in Celsius.

Solution: The converting formula for the two scales is °F = 1.8°C + 32.
That is, °C = (°F -32) / 1.8. So, 98.6°F is (98.6 – 32) / 1.8 = 37°C.
98.2°F is (98.2 – 32) / 1.8 = 36.778°C. The difference is 37 – 36.78 = 0.22°C.

In the scientific world, the Kelvin temperature scale, or absolute temperature, has more meaning. This is the SI unit for temperature, and it is defined as 1 K is 1/273.16 of the thermodynamic temperature of the triple point of water at which the three phases coexist with equilibrium.

From the ideal gas law PV = const.*T. If the volume is not changing, the pressure (P) is directly proportional to the temperature (T). That is, we can use this relation to indicate temperature while adjusting the pressure of the gas container. If we plot between the temperature (T) and the pressure (P), the result indicates that -273.15°C, absolute zero points, has an important value because it is the corresponding value when the pressure is zero. It is impossible to reach lower than the absolute zero points, 0 K, the lowest temperature. The relation between the Celsius scale and the Kelvin scale is K = °C + 273.15.

A Weird Property of Water

Most substances contract as the temperature decreases and expand as the temperature increases; however, this is not the case for water. As the temperature decreases from room temperature (20°C = 68°F), water contracts until the temperature arrives at 4°C (= 39.2°F), and then it begins to expand as the temperature decreases to below 4°C. This is a unique characteristic of water.

It has the maximum density (or minimum volume) at 4°C, not 0°C (= 32°F; freezing temperature) so organisms in the water can survive! Let's consider a lake in winter. As the temperature decreases to 4°C, the top surface of the water is denser, so it goes down to the bottom. The next warm layer of water is now at the top surface of the water, and when this layer's temperature drops toward 4°C, it will sink. This process will continue until the entire lake's temperature is 4°C.

As the air temperature decreases further, the density of the surface of the water in the lake will decrease, but the volume increases. No more sinking business occurs. The surface water is freezing when the temperature decreases to 0°C. That is, ice is forming on the surface, but under the surface, water is not freezing at all due to the special property of water. In fact, the role of the sheet of ice on the top surface of the lake is to be an insulator to preserve heat under it, so fish can live even though it is cold outside.

Heat and Internal Energy

An object has internal energy that is proportional to the temperature. The internal energy is the total energy of the object due to the molecular random motion, forces between molecules or atoms, and so on. Neglecting the work done, the internal energy of the hot object decreases and that of the cold object increases as heat transfers.

The heat (*Q*) must be added or removed to change the temperature of a material of mass (*m*): $Q = cm\, dT$, where *c* is the specific heat capacity, and *dT* is the temperature difference.

Sample Question 4: Suppose 0.5 kg of blood flows from the interior to the surface of John's body while he is exercising. The released energy is 2000 J. The specific heat capacity of blood is 4186 J / kg^{o}C. What is the temperature difference between when the blood arrives at the body surface and returns back to the interior of the body?

Solution: Use the formula, $Q = cm\, dT$. Here, the specific heat capacity *c* is given as 4186 J / kg^{o}C. The mass *m* is 0.5 kg. *Q* is 2000 J. So, the temperature difference $dT = Q / cm = 2000 / (4186 \times 0.5) = 0.96^{o}C$.

Heat and Phase Change

As the heat is added to or removed from a material, the internal energy varies, which causes a change in temperature or a change in phase. However, it is possible to maintain a constant temperature whether the heat is added or not. Consider a cup of water with ice in a warmer room. See Figure 12.27 in Section 12.8 of Chapter 12 in the eTextbook (Cutnell et al., 2022) for a graphic representation of the energy involved in the phase changes of water.

The heat will be added to the cup, but the temperature does not increase above 0^{o}C as long as there are ice cubes. In fact, the heat is used to melt the ice. When the ice is completely melted, the temperature is now increasing. The heat (*Q*) used to change from one phase to another phase of the matter is $Q = mL$, where *L* is the latent heat. Its unit is J / kg.

The latent heat of fusion refers to the change between solid and liquid phases. The latent heat of vaporization refers to the change between liquid and solid phases, and the latent heat of sublimation refers to the change between solid and gas phases. See Figure 12.26 in Section 12.8 of Chapter 12 in the eTextbook (Cutnell et al., 2022) for the phase changes between any two of the three phases of matter.

Sample Question 5: How much energy is needed to change 100 g of 0^{o}C ice to 0^{o}C water? The latent heat of fusion for water *L* = 335,000 J / kg.

Solution: The heat (*Q*) used to change from one phase to another phase of the matter is $Q = mL$, where *L* is the latent heat. Its unit is J / kg. Here, the mass *m* is given as 100g = 0.1 kg. The latent heat *L* is given as 335,000 J / kg. So, the energy needed is $Q = mL = 0.1 \times 335000 = 33500$ J.

Reference

Cutnell, J. D., Johnson, K. W., Young, D., & Stadler, S. (2022). *Physics* (12th ed.). Wiley.

Learning Activities (Nongraded)

Nongraded Learning Activities are provided to aid students in their course of study. You do not have to submit them. If you have questions, contact your instructor for further guidance and information.

1. Solve Questions 77–94 under Physics in Biology, Medicine, and Sports in Chapter 11 of your eTextbook.
2. Solve Questions 82–93 under Physics in Biology, Medicine, and Sports in Chapter 12 of your eTextbook.