Lab 12

Buoyant Force and Archimedes Principle

Learning Objectives

- Predict the behavior of fluids as a result of properties including viscosity and density

- Demonstrate why objects sink or float

- Apply Archimedes Principle by measuring buoyant force and weight of water displaced

- Apply Archimedes Principle to calculate the density of a material

Introduction

The properties of a fluid determine its behavior and can be harnessed for many commercial uses including fluids used in vehicles and watercraft design. The utility of properties of fluids can even be observed in biological examples. Unlike solid materials, which maintain steady shape and volume, **fluids** can easily deform. This allows them to "flow" around surfaces and take on the shape of any volume they fill (Figure 1). Gases and liquids are considered fluids.

Figure 1: The liquid water in this dam takes on the shape of the reservoir in which it is stored. If the flood gates were opened, water would flow out following a path of least resistance.

Pascal's Principle

One the most important concepts to understand when studying fluids is pressure. **Pressure, P,** is a ratio of force, F, applied over an area, A:

$$P = \frac{F}{A}$$

The SI unit for pressure is the pascal or Pa (1 Pa = 1 N/m^2). Fluids freely flow under the presence of sheer stress because they have no rigid structure. As a result of this property, fluids exert pressure in all directions if the fluid is not moving, or static. Another property of fluids in a static condition is that they exert pressure perpendicular to any surfaces with which they are in contact. If they didn't, the reaction force of the surface would cause a flow in one direction.

A SCUBA diver or swimmer feels the effect of pressure as the depth of travel increases. As a diver descends to deeper water, the amount of water on top of the diver increases. The increase in the weight of the water causes a proportional increase in pressure. The result causes a noticeable force on the diver's eardrum (along with the rest of the body). The same effect can be observed in an airplane when air pressure decreases as altitude increases. The equation that relates hydrostatic pressure to depth is:

$$P = \rho gh + P_{atm}$$

where ρ is the density of the fluid, h is the distance below the fluid surface, and P_{atm} is the pressure of the atmosphere above the fluid surface.

Density (kg/m^3) is an important quantity when analyzing the interaction of objects in fluids and is a measure of a substance's mass divided by its volume.

Buoyancy

Buoyancy is what allows objects, like massive cruise liners, to float on the surface of oceans and lakes. This phenomenon is a result of hydrostatic pressure. For an object submerged in a fluid, the bottom of the object at a greater depth will experience more pressure than the top of the object. The result is a net upward force on the bottom of the object called **buoyant force** (Figure 2). If you have ever tried diving to the bottom of a deep swimming pool, you have probably noticed that it is hard to stay submerged, yet near the shallow end, it is easy to sink down to the bottom. This is explained by buoyant force. The deeper the object, the larger the buoyant force.
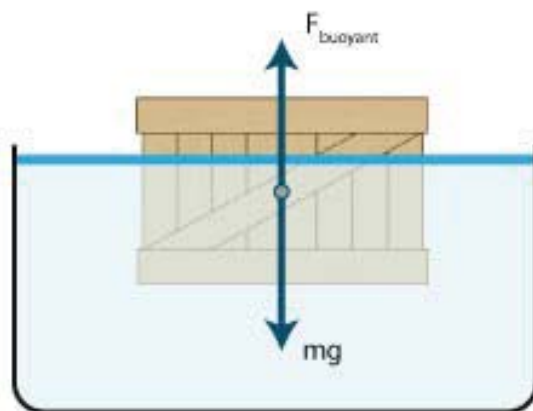
Figure 2: The free body diagram of a floating object shows equal and opposite forces of buoyancy and weight.

Archimedes Principle

Archimedes, a Greek philosopher, who lived during the third century B.C., was one of the first to explore this phenomenon. **Archimedes Principle** states that the buoyant force on an object in a fluid is equal to the weight of the volume of fluid it displaces. This explains how even massive ships stay afloat (Figure 3); while the ship is a very heavy object, the weight of the water displaced by its hollow hull is much heavier. Archimedes Principle can be represented by the mathematical relationship:

Figure 3: This huge oil tanker stays afloat because it displaces more than its own weight in water!

$$F_{buoyant} = m_{fluid}g$$

Since the mass of the fluid displaced is equal to its density multiplied by it volume, the mass, m, in the equation above can be replaced by ρV. This volume is the same as the volume of the object submerged. The buoyant force can then be written as a function of fluid density and volume:

$$F_{buoyant} = \rho g V$$

Archimedes Principle also states the conditions necessary for an object to float in a fluid. If an object is floating, the buoyant force must be greater than or equal to the weight of the object:

$$m_{object} \leq m_{fluid}\ displaced$$

Since the volume of the object and fluid displaced are equal, if the object is completely submerged, the object's density must be lower than the fluids, or:

$$\rho_{object} \leq \rho_{fluid}$$

If an object has a low enough density, only part of its submerged volume provides enough buoyant force to float. In this case, part of the object will remain above the surface of the fluid.

Viscosity

The velocity of a fluid depends on what is called its **viscosity** which is the amount of internal friction within a fluid that prevents it from easily flowing. Water has a relatively low viscosity compared to corn syrup, which slowly drips out of its container even when turned upside-down. Viscosity also affects how easily an object can move through a liquid – imagine how difficult it would be to paddle through a lake composed of thick molasses!

Pre-Lab Questions

1. Draw a free body diagram of a hanging mass before it is submerged in water. Make sure to label your forces.

2. Draw a free body diagram of a hanging mass after it is submerged in water. Make sure to label your forces. Which force is measured with the spring scale?

3. Apply Newton's Second Law to your free body diagram in Pre-Lab Question 2 to solve for the magnitude of the buoyant force. Show your work.

4. A wooden crate, made from wood with density ρ_w, is floating on a liquid with density ρ_l.

   a. Formulate a general equation for the depth the crate is submerged, h, if the crate has a length, L, width, W, and height, H. Write your equation in variable form.

b. Solve for the depth the crate is submerged if ρ_w = 670 kg/m³, ρ_l = 1100 kg/m³, L = 10 m, W = 7.0 m, and H = 5.0 m.

5. If the wooden crate is submerged under the water,

   a. Derive a general equation for the acceleration of the box after it is released. Show your work.

   b. Determine the acceleration of the wooden crate for the values given in Pre-Lab Question 4. Show your work.

Experiment 1: Effects of Density

In this experiment, you will observe how the density of various materials affects their vertical arrangement in a density column. You will also observe the behavior of ice and water and draw conclusions about the molecular arrangement of each. By definition, water has a density of 1 g/cm³. However, the density of every liquid is not the same. This principle is often used in the oil industry to separate hydrocarbons from water. Some liquids, like oil, have densities of around 0.91 g/cm³. Such a liquid will float on water because it is less dense. Solids also have varying densities, causing them to either float or sink in water.

⚗ Materials

(1) 100 mL Beaker	1 Plastic Coffee Lid
(1) 250 mL Beaker	Scissors
50 mL Cooking Oil	1 Washer
1 Cork	*100 mL Water
50 mL Corn Syrup	
1 Drop Food Coloring	*You Must Provide
(1) 100 mL Graduated Cylinder	

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Procedure

1. Use the graduated cylinder to measure and pour 100 mL of water into the 100 mL beaker.

2. Add one drop of food coloring to distinguish it from the other liquids.

3. Pour the water into a 250 mL.

4. Use the 100 mL graduated cylinder to measure 50 mL of corn syrup and pour it into the 250 mL beaker.

5. Use the 100 mL graduated cylinder to measure 50 mL of cooking oil and slowly pour it into the 250 mL beaker.

6. Once all liquids have been added, allow the contents of the beaker settle for a few minutes. Observe and record the order of the different liquids in Post-Lab Question 1.

7. Use the scissors to carefully cut the plastic coffee lid into four equal pieces.

8. Carefully, without splashing the liquids drop the washer, $1/4$ of the plastic coffee lid, and the cork into the beaker. Observe what liquid each object settles in. Record your observations in Post-Lab Question1.

Post-Lab Questions

1. Sketch and label the arrangement of objects and liquids in the beaker.

2. Rank the liquids and solids in order of least to most dense and use your results to explain your reasoning.

3. Explain which of the solid materials used in this experiment would make the best boat. Use your results to support your answer.

4. Would it be easier to design a boat in a world with oceans of maple syrup than oceans of saltwater? What property of maple syrup might prevent boats from traveling in it very effectively compared with in water?

Experiment 2: Buoyant Force and Floating

Have you ever wondered why you feel weightless in water? If you have spent enough time in the pool, you will know that it is possible to lift heavy objects underwater (like a person) that would require much more effort to lift on land. This phenomenon is due to the effect of the buoyant force that acts on solids submerged in liquids. In this experiment, you will explore the science behind why objects seem lighter in water and will explain this reduction in weight using Archimedes' Principle. You will also examine buoyancy in a solution of salt water and compare it to that in plain water and will explain your observations in terms of density.

⚗ Materials

(1) 250 mL Beaker	Wooden Stir Stick
(1) 100 mL Graduated Cylinder	*Paper Towels
Measuring Spoon	*Water
5 tsp. Salt, NaCl	
$^1/_2$ Stick Modeling Clay	*You Must Provide
15 Washers	

Procedure

1. Use the 100 mL graduated cylinder to measure and pour 150 mL of water into a 250 mL beaker.
2. Take a ½ stick of modeling clay and divide it into two equal pieces so that the masses are equal.
3. Roll one piece into a ball and place it in the beaker. Observe the buoyancy of the ball. Record your observations in Post-Lab Question 1.
4. Remove the ball from the beaker.
5. Design a shape for a clay boat so that the boat will float.
6. Use the remaining clay to form your boat design. Remember, you want the buoyant force to be large, along with a shape that won't tip over.
7. Place your boat in the beaker and observe what happens. If your boat doesn't float, try out different shapes until you are successful. Use these observations to answer Post-Lab Question 2.
8. Once you have designed and built a boat that floats, add metal washers to the boat, one by one. Record how many washers you can add before the boat sinks in Table 1.
9. Remove the boat and washers, mix five teaspoons of salt into your beaker, stir well with a wooden stir stick to ensure the salt is even dissolved in the water and repeat Step 8.

Table 1: Number of Washers a Clay Boat Can Hold Before Sinking	
Type of Liquid	**Number of Washers**
Plain Water	
Salt Water	

Post-Lab Questions

1. What did you observe when you placed the ball of clay into the beaker?

2. What were characteristics of the boat design that floated the best? Use Archimedes' Principle to explain why these design characteristics cause the boat to float, and the clay ball to sink.

3. If your clay boat weighs .005 kg and is floating, what is the upward force the water is exerting on the boat?

4. How could you improve your boat design to increase the buoyant force without using more clay?

5. In the second part of the experiment, does the boat hold more weight in the regular water or the salt mixture? What can you infer about the relative densities of salt water and plain water? Use your results to support your answer.

6. How much water does an object have to displace before it will float?

Experiment 3: Buoyant Force and Archimedes Principle

In this experiment, you will investigate the effect fluids have on the weight of submerged objects.

⚗ Materials

(1) 250 mL Beaker	Vernier Caliper
1 Catch Pan	*Paper Towels
(1) 100 mL Graduated Cylinder	*Water
(1) 250 g Hanging Mass	
5 N Spring Scale	*You Must Provide
Short String	

Procedure

1. Use the Vernier caliper to measure the base edge (length of one side of the hexagon) and height of the 250 g hanging mass. Record the values in Table 2.
2. Place a 250 mL beaker on the catch pan.
3. Fill the 250 mL beaker to the brim with water. Be careful not to spill any water in the catch pan. If water does spill, use a paper towel to clean it up and make sure the beaker is completely full of water.
4. Tie one end of a string to the 250 g hanging mass and the other end to the spring scale. Suspend the hanging mass in the air and record its weight in Table 3.
5. Slowly submerge the hanging mass under water being careful not to let the hanging mass touch the sides or bottom of the beaker. The water will overflow into the catch pan.
6. Try to keep your hand as stable as possible to keep the hanging mass stationary in the water. Record the weight of the mass in water in Table 3.
7. Slowly raise the mass out of the water. Be sure not to spill any extra water into the catch pan. Set the hanging mass down away from the catch pan and remove the beaker from the catch pan.
8. Carefully pour the water from the catch pan into the 100 mL graduated cylinder and record the volume of displaced water.
9. Calculate the buoyant force acting on the mass by subtracting the mass's weight in water from the mass's weight in air. Record the buoyant force in Table 3.
10. Repeat Steps 2 - 9 with the rubber stopper.

Table 2: Dimensions of 250 g Hanging Mass	
Base Edge (cm)	**Height (cm)**

Table 3: 250 g Hanging Mass Buoyancy Data				
Object	Weight in Air (N)	Weight in Water (N)	Buoyant Force (N)	Volume Displaced (mL)
250 g Hanging Mass				

Post-Lab Questions

1. What happens to the apparent weight when the mass is submerged in water?

2. Use the value of the buoyant force to calculate an experimental value of the volume of the 250 g mass in kg/m^3 ($F_b = \rho_L V_D g$). The density of water is approximately 1000 kg/m^3. Show your work.

3. Use the measured dimensions of the 250 g mass to calculate the volume of the mass, $V = \dfrac{3\sqrt{3}}{2} b^2 h$. Show your work.

4. Determine the percent difference between the measured volume of the 250 g mass and the value calculated from the buoyant force measurement. Show your work.

5. Using the fact that 1 mL = 1 x 10^{-6} m^3, compare the volume of the displaced water to the calculated volume of the mass from Post-Lab Question 3 with a percent error calculation. Show your work.

6. Are the experimental values of the volume of the 250 g mass (from Archimedes' Principle) larger or smaller than the calculated value using the caliper measurements? Why? Which of the three values for volume is more accurate? Which of the two experimental volumes are more accurate? Explain.

7. Does the data support Archimedes' Principle? Why or why not?

8. Identify two possible sources of error in the experiment. How could the procedure be revised to remove these potential errors?

Experiment 4: Design Your Own Experiment

Design your own experiment to use the concept of buoyant force and Archimedes' Principle that you practiced in Experiment 3: Buoyant Force and Archimedes' Principle. For this experiment, you have been provided with a #6 rubber stopper. Use the experimental principles you have learned in this lab to determine the density of the rubber material of the #6 rubber stopper. You should not need any other materials than the materials provided to you in this lab.

IMPORTANT: Students must submit personally designed experimental procedures to a teacher for approval prior to performing the experiment.

When designing your experiment, create a hypothesis, identify dependent and independent variables, identify controls, include calculations where useful, record appropriate data, and report important data in an organized manner (blueprints and free body diagrams). After completing your experiment, write a brief post-lab report in which you address your hypothesis, procedure, data, calculations, data analysis, potential sources of error, conclusion and additional questions or "next-steps".