Density, Buoyancy, and The Plimsoll Mark

Introduction

Why do we wear PFD's (personal flotation devices, also known as life jackets) when we ride on a boat? How is the Knock Nevis, the largest ship in the world and weighing 647,995 tons when fully loaded with petroleum, able to float with no problem? It all has to do with buoyancy.

Buoyancy is the upward force exerted on an object by the surrounding fluid (in most cases, water) in which the object is immersed.

Buoyancy acts against the force of gravity. If the density of the object is greater than that of the surrounding fluid, the object sinks. If the densities are equal, the object is neutrally buoyant and hovers in the fluid. If the density of the object is less than that of the surrounding fluid, the object floats.

So although the human body can typically float in water because of the air in the lungs, a person wearing a properly-fitting, well-maintained PFD, the density of which is extremely low, is practically guaranteed to float.

Density is defined as the mass per unit volume of an object (D = M / V). Remember that mass is not the same as weight. A small but heavy object, such as a lead fishing sinker, is denser than a lighter object of the same size, such as a cork. The same holds for a bowling ball vs. a soccer ball. Both are relatively the same size, however, the bowling ball has much more matter. Mass is how much matter there is in an object, and is measured in kilograms (kg). Weight is the size of the gravitational pull on an object, and is measured in units of force, such as (kg•m/s2), which is usually simplified to just kg. Weight is calculated by multiplying mass and acceleration due to gravity. Different fluids have different densities. Since oil is less dense than water it floats on water.

Question 1: *The density of a substance is 1.63 g/mL. What is the mass of 0.25 L of the substance in grams? (Hint: use unit conversions)*

The density of a fluid is affected by several variables, including temperature and salinity. As a fluid's temperature increases, its density decreases. Conversely, as a fluid's salinity increases, so does its density. Therefore, colder salt water will sink below warmer, freshwater. Because saltwater is denser (1025 kg/m3) than fresh (1000 kg/m3), objects, including humans, are better able to float in saltwater.

Question 2: *Two liquids, A and B, have densities 0.75 g/mL and 1.14 g/mL respectively. When both liquids are poured into a container, one liquid floats on top of the other. Which liquid is on top?*

Question 3: *A piece of wood has a mass of 25.0 grams and a volume of 29.4 cm^3. Will this object float or sink in freshwater? (Hint: Convert your answer to kg/m^3)*

So how exactly does a huge cargo ship stay positively buoyant, even when fully loaded? The key is to ensure that the volume of the ship is large enough to displace the mass of the ship. In the 3rd century BC, the Greek mathematician Archimedes realized that when he got into his bathtub, his body displaced the water making it rise and spill out of the tub. His discovery led to two laws of buoyancy that are still the basis of today's shipbuilding. His first law states that any floating object displaces a volume of water whose mass is equal to the mass of the object. The second law describes the effect a boat's shape has on how well it floats.

In addition to its shape, another important component of a commercial ship is the Plimsoll mark. Named for Samuel Plimsoll, these markings are not only painted, but permanently welded mid- ship onto both sides of a ship's hull. This important visual cue helps ensure the ship is loaded evenly and not overloaded for the water conditions through which the ship will be sailing. Safety is the main premise behind the Plimsoll mark.

Here are the definitions for the markings on the Plimsoll mark. In this figure, the two lines pointing left represent freshwater and the four on the right represent saltwater. The circle with the line through it indicates whether or not the cargo is loaded evenly (bow too heavy/light, etc.). Because saltwater is denser than freshwater, regardless of the water depth, ships will float lower in freshwater than in saltwater. If they are not loaded properly and encounter less dense water, they may float too low. When floating lower in the water, the ship's risk of becoming unstable increases, a dangerous situation if the ship encounters heavy seas. There is also a risk that the ship can run aground in less dense water.

The Plimsoll mark is very easy to use and effective in keeping ships and their crews safe. A ship is loaded according to the type of water in which it is being loaded. If loaded until the water line reaches the appropriate Plimsoll line, it can safely travel through all of the different densities of water on the planet! If the ship is loaded beyond the correct line, its chances of a safe voyage are lessened. For example, if a ship in Norfolk, VA is loaded in January to the “F" line and travels to the much warmer (and thus, less dense) waters of Puerto Limon, Costa Rica, the ship will be floating dangerously low; whereas, if the ship is properly loaded to the “W" line, it will maintain a safe floating height when it sails into the southwest Caribbean.

Data Activity

A. Investigating Ship Attributes

So how are giant cargo ships able to float? First, we need to explore how big these ships really are.

Ships can be classified several different ways according to their different attributes, including their: volume, length, draft (amount of ship below the water line) and cargo capacity. Cargo capacity is typically measured in TEUs, or twenty-foot equivalent units, which represents the number of 20 foot containers a ship can hold.

To explore these attributes, let’s look at them using a cargo ship that is infamous among oceanographers, the M/V (motor vessel) Ocean Hope, formerly the M/V Hansa Carrier. In 1990, the Hansa Carrier encountered rough seas in the Pacific Ocean on its way from Korea to the United States and lost 21 of its 40-foot containers. Loaded in 5 of these containers were Nike
shoes – over 80,000 of them – which subsequently contributed to an unplanned oceanography experiment that is still active today.

- Use Figures 1a and b to fill in Table 1.

B. Understanding the Plimsoll Mark

Using the information learned above, fill in the Plimsoll mark worksheet and answer the following questions.

Question 4. In terms of density, why would a ship float lower in "T" water than in "W" water?

Question 5. The ship in Figure 2 is being loaded in Philadelphia, PA *(fresh water)* for its trip to Miami, FL. Has it been overloaded with cargo? How do you know?

Use Figures 3a-c to answer the following questions.

Question 6. The ship in Figure 3a just left port (tropical freshwater) after being loaded with cargo, why will the captain's boss be upset with him? Why is this a potentially dangerous situation?

Question 7. What is wrong with the ship in Figure 3b? Can you offer some suggestions as to why this happened?

Question 8. What is the problem in Figure 3c? How can it be fixed?

C. Hindcasting (evaluating archived data) Accessibility of the York River, VA by the M/V Ocean Hope The *M/V Ocean Hope* does not sail in the York River, but this vessel serves as a good example of a typical large ocean-going vessel, so we will use it in the following activities. Using archived data sets from the VIMS NOMAD buoy, located at the mouth of the York River, you will determine whether the river is deep enough for the M/V Ocean Hope to enter and deliver its cargo. The NOMAD buoys measure a suite of abiotic parameters including wave height, wave period, salinity and water depth.

Refer to your Table 1 of vessel attributes and view Figure 4, a graph of mean water depth data from the week of October 29 to November 5, 2007.

From the figure:

Question 9. What is the range in water depth?

Question 10. Why does the water depth increase and decrease daily?

Question 11. On what day was the water the deepest?

Question 12. On what day was the water the shallowest?

Question 13. Provided the M/V Ocean Hope was loaded properly, could it enter the York River whenever it wanted during the week shown?

- **A.** If not, is there any point during the week that the ship could enter the river and not scrape the bottom (water depth > 10.6m)? If so, when?

- **B.** For each date, about how much clearance would there be between the hull of the ship and the sea floor?

Question 14. The average temperature and salinity of the York River during this time period were 13.8 degrees C and 22.8 ppt, respectively. If the M/V Ocean Hope was loaded properly in its departure port and had enough water to sail in the York, where would the water line be on its Plimsoll mark?

Now view Figure 5, a graph of the mean water depth data from the year beginning on November 5, 2006.

Question 15. What is the range in water depth?

Question 16. During what month was the water the deepest?

Question 17. During what month was the water the shallowest?

Question 18. During what season is the *M/V Ocean Hope* most likely to encounter water deep enough to enter the York River?

- **A.** Formulate a hypothesis to explain this observation.

- **B.** The U.S. Coast guard stipulates that in order for a ship to enter a channel or port, there must be 2-3 feet of water between the bottom of ship's hull and the sea floor. With this regulation in mind, is the water at the mouth of the York River ever deep enough for the M/V Ocean Hope to legally enter? *Note: You must convert the depth from meters to feet (1 foot = 0.305 meters)*

Application Questions

Question 19. The salinity at the mouth of the York River is typically between 15-22 ppt. Will the Ocean Hope float higher or lower in the water if there was a big rain storm which dropped the salinity to 9-13 ppt? *(Draw a Plimsoll mark if it will help!)*

Question 20. If the above rain storm was part of a strong cold front that dropped the water temperature by 5 degrees C, what effect would this have on how high or low the ship floated? *(Draw a Plimsoll mark if it will help!)*

Evaluating Density Plots

The Rutgers University Coastal Ocean Observation Laboratory (COOL) utilizes a fleet of autonomous underwater vehicles (AUVs) called gliders that “fly" through the water column in a zig-zag pattern (up and down) recording data such as salinity, temperature, chlorophyll, sound velocity, and more. Gliders are a buoyancy lesson in themselves, as they change their density in order to move up or down through the water column. As we learned above, salinity and temperature both have a substantial effect on the density of water, and subsequently on many other parameters. The COOL posts plots of these data in real-time and then archives them once the glider mission is complete. In this section of the activity, we will analyze several density plots.

View Extension Figure 1 and Figure 2; salinity, temperature, density plots, and transect maps from two COOL glider missions and fill in the data for Extension Table 1. *Note: On the transect maps, the start point is indicated by the green dot, and the stop point is the red dot.*

- Considering the entire water column, do Figures 1-2 appear normal (i.e. colder water is below warmer water and higher salinity water is below lower salinity water)? Why or why not? Be specific.
- Consider your answers in Column F. If the highest salinity recordings were in the same area of the figure as the lowest temperature recordings, what would you expect the density plot to look like?
- Explain how do you think it would be possible for saltier water to exist overtop less salty water?