Water Density

For most normal substances, as heat is removed from the molecules, they are able to get closer together and become denser. And the solid form is the most dense form. However, water behaves much differently as we know well from having our solid ice cubes float atop our liquid sodas. The solid form of water – ice –is LESS dense than the liquid form Why? The shape of the water molecule of course. As long as water molecules have enough velocity, they can slide in and around each other. However, when they slow down enough, they pack together in a hexagonal structure based on hydrogen bonding. This structure leaves a large hole in the middle of every six water molecules and thus produces a more expanded less dense form. Let's look at that more closely.

Once water cools to very near its freezing temperature (zero degrees), it starts to develop zones of crystals in the hexagonal arrangement previously described – the ones that actually take up more space than the liquid form. When does that start to happen? About 4 degrees Celsius. The result? The liquid starts to expand. The water becomes less dense and rises!. And when, at zero degrees Celsius, it completely freezes, it's now made up of 100% of that expanded crystal structure, and it is so low density that it floats. This behavior is important for natural freshwater bodies on land. It's what allows fish to survive winter in the bottom of lakes that are frozen. If ice was denser than water, then lakes would freeze from the bottom upwards, and fish would get frozen out of the lakes. Because, however, freshwater below 4 degrees Celsius is LESS dense than 4 degrees Celsius water, whenever the coldest water in the lake (usually the bottom water), gets colder than 4 degrees Celsius, it starts to rise where it either warms up or freezes and creates an ice cover. Thus, lakes freeze from the top down and are more likely, if deep enough, to retain pockets of warmer water beneath the ice for fish.

These molecules of water demonstrate what happens as water moves from solid to liquid to gas and back again. Notice the orderly arrangement of the solid and the big space left in the middle.

Freshwater is the standard against which the density of all other materials are measured. The SI system of units – including grams and Liters was developed around water. The definition of 1 gram is the amount 1 cubic centimeter or 1 milliliter of freshwater weighs at 4 degrees Celsius at sea level.

This chart compares the temperature of water to its density (notice the X-axis shows water temperature decreasing to the left, and the Y-axis shows density decreasing as we move down). The red line shows how the density of water changes as the temperature changes. Starting on the right, we see that 20 degree Celsius water is less dense than water at 4 degrees Celsius. This is what we would expect, as raising temperature means higher Kinetic Energy, which means atoms can move further apart. As temperature decreases, the atoms get closer together, and become more compact or dense. However, as we already discussed and as this graph makes clear, when we cool below 4 degrees Celsius, some of the water molecules get close enough together that they begin to form the orderly hexagonal pattern they will have asa solid and the density starts to drop.

Here is a list of the density of other common materials. Notice that ice is less dense: 0.917 grams per cubic centimeter. Olive oil is less dense as well. That's why it floats on water. Alcohol is even less dense, which is why alcohol floats on olive oil. Also, notice how much denser metals are. And finally, notice that seawater is denser than freshwater. Why? Let's look more closely at that question.

There are two ways to change the density of water. One is through temperature as we've already discussed. The other is through the addition of dissolved ions. **Salinity** is a measurement of the percentage of dissolved ions in a body of water. The higher the salinity, the denser the water. This picture shows swimmers in the Dead Sea, a highly salty body of water in the Middle East. Because of its salinity, this water is extremely dense. You can tell that because the swimmers are floating much higher in the water than they normally would. How high something floats atop another substance is a good measurement of the difference in density between the two. As long as you know the density of one of the substances, you can use the float level as a way of determining the density of the other. We use a device called a **hydrometer** to measure the density of water, based on how high it floats. The higher this device floats in the water, the denser the fluid is and the larger the number that will register at the water line.

So why is saltier water denser? The heavy ions that are trapped within hydration spheres add to the mass without changing the volume. That increases density. You can test this yourself by adding salt to water and letting it dissolve. The volume of water will NOT change, but the salt crystals will disappear. Why? They've been surrounded by polar water molecules and pulled apart as discussed earlier. Of course, once water molecules are busy separating dissolved ions, what happens to water's ability to hydrogen bond to itself? It decreases That means that as you cool the water, and all the molecules and ions slow down, they still remained trapped in hydration spheres. It's harder to create hexagonal patterns. Not only does that cause the freezing point to lower, but it also eventually eliminates the the density inversion below 4 degrees. Let's look at that more closely.

This graph shows exactly at what salinity the density inversion disappears. Here Temperature increases as we move up on the Y axis, while salinity increases as we move right on the X axis. The black line shows the melting temperature of water. For pure water (0 dissolved ions), the melting temperature is what we know it to be: 0 degrees Celsius. Notice that as salinity increases, the melting point lowers. Seawater, with an average salinity of 35 parts per thousand corresponds to a melting temperature of about -1.5°C. The red line shows the temperature of maximum density of freshwater. Notice that for pure water it has a maximum at 4 degrees Celsius. However, as salinity increases, not only does freezing point drop, but so too does the maximum density temperature. Why? It's harder for water to hydrogen bond to itself when there's a lot of dissolved ions trapped in hydration spheres. However, the maximum density temperature is dropping FASTER than the freezing temperature. So, by about 25 parts per thousand salinity, the density inversion entirely disappears. All water with higher salinity – including all ocean water – will simply get denser as it cools all the way until it freezes. What happens then? When seawater freezes, it's only the water molecules that bond to each other. The dissolved ions will be left behind in a super salty brine, and the ice will be pure, less dense, and float atop the icy brine. Where does this happen? At the poles.

The cold temperatures of the poles lead the seawater there to be the highest density in the world. These pictures show an interesting phenomenon that takes place under the Antarctic ice sheet. As ice forms at the surface the ions that are forced out saturate the surrounding water creating pockets of super-salty brines. Their freezing temperature drops substantially below that of normal seawater – which allows them to get as cold as -6 or 7 degrees Celsius. The highly dense cold and salty brines drill down through the ice and when they meet the normal seawater underneath, with a normal melting/freezing point of -1.5 degrees Celsius, the much colder brines cause the first water they touch to freeze. The result is the formation of a hollow tube of ice as the brines descend. The tube is made of frozen normal seawater. Within it descends the super salty brines from above. You can see what happens to these fluids as they hit the seafloor – they don't mix easily because their density is so much higher than the surrounding water. Instead they stay on the bottom and spread out across the seafloor.

This same thing happens on a larger scale in the oceans as a whole. This bathtub cross-section of the oceans shows the equator in the middle, the Arctic on the left, and the Antarctic on the right. Notice that ALL the deep water in the world's oceans is formed by cold dense waters in the poles sinking and spreading out laterally. What's left is a thinner layer of warmer surface water sitting over cold dense polar waters. Even at the equator, where the surface waters can be quite warm, the water at depth is cold polar water. The boundary between these two water layers is called the a pycnocline – pycno means density – cline means changing. It is the zone where the density changes substantially from the surface layer to the deep layer beneath.

The Rio Negro is a tributary of the Amazon River. It is dark brown because of all the dead vegetation that seeps into it from the rain forest. The Rio Solimoes is a milky tan color because of all the sediment it has collected in the Andes mountains. Amazingly, these two bodies of water don't mix for 6 miles, because of their differing density.

San Francisco Bay combines seawater that comes in under the Golden Gate Bridge with freshwater that comes in from the Sacramento River. Where the two meet there is partial mixing. The denser saltwater partially wedges itself under the less dense freshwater which sits atop it. There are parts of the North Bay where you can be in a boat in fresh water at the surface and drop a fishing line down to a depth that's almost all saltwater.

We will talk more about all these concepts in the next few weeks. But it's important to know right now how much of the mixing in the oceans is driven by density.

Pause now.

For more information and more detail, continue on to the next video in this series.

[End credits]

Seawater Physical Properties Series:
Part I: Water Molecule Shape
Part II: Water Phases
Part III: Water Density
Part IV: Heats of Water
Part V: Light, Viscosity, & Pressure
Part VI: Heat Transfer

Water Density
Geoscience Video Tutorial
Produced by Katryn Wiese
City College of San Francisco

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