Fluids at Rest: Crash Course Physics #14

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I think fluids are fascinating and awesome, because they happen to be my area of expertise as an engineer in fluid dynamics. But it's not just me who's intrigued by how things flow - legend has it that a man once ran naked through the streets, because he was so excited about discovering an important property of fluids.

Now, I've never quite gone that far, but still - an understanding of fluids is incredibly useful, because anything that flows - liquid or gas - is a fluid. So water counts, but so does air. And so does corn syrup.

Using their knowledge of fluids, physicists and engineers can design things like pressure sensors, hydraulic pumps, and even airplanes. But first, let's start with the basics - the physics of fluids at rest.

-- Intro Song --

Until now, we've often described the physics of objects based on their mass, but when it comes to fluids, we mostly use a different quality - density, represented in equations by the Greek letter rho.

You're probably familiar with density - it's mass divided by volume, and measured in kilograms per metres cubed. If an object or a fluid is made of heavier atoms or molecules, or those particles are packed more closely together, then it's going to have a higher density.

And there's another important quality of fluids, one that scuba divers and mountain climbers think about a lot - pressure. In our last episode, we defined pressure as applied force divided by area. It's measured in units of Newtons per metre squared, known as Pascals. And fluids apply pressure in every direction, so right now, there's air putting pressure on you and me from every side. In fact, the average air pressure at sea level is 101,325 Pascals.

And if you jumped in a pool, the water would also exert pressure on you, but if you've ever tried diving to the bottom of a pool, you'll know that there's more pressure at the bottom than at the surface, which is why at the bottom, your ears hurt and your head feels like it's about to implode! That's because the deeper you go, the more fluid there is above you, with its weight pressing down.

There's an easy way to calculate the pressure of a fluid at a given depth: it's just the fluid's density times small *g* times the distance to the surface (represented by the letter *h* for height). And the change in pressure based on depth is equal to the fluid's density times small *g* times the change in distance to the surface.

So let's say you're swimming in a pool that's three metres deep, and you want to know how much more pressure you'll experience at the bottom of the pool versus how deep you are now, which is, let's assume, a quarter of a metre. The density of the water is a thousand kilograms per metres cubed, and the change in distance to the surface is 2.75 metres. Which means that the pressure at the bottom of the pool is 27,000 Pascals more than the pressure at a quarter of a metre down.

The water in the pool could be one example of a confined fluid, because if you had a piston the size of the pool's surface and used it to push down on the water, the water would have nowhere to go.

Back in the mid-1600s, French physicist Blaise Pascal realized something about the way pressure worked in confined fluids. If you apply pressure to a confined fluid, the pressure in every part of the fluid increases by that amount. If you have water in a cup, and you use a piston to apply 10,000 Pascals of pressure to the surface of the water, then the pressure everywhere in the water increases by 10,000 Pascals. Today, that concept is known as Pascal's Principle, and it's the reason hydraulics are so useful.

Say you have some water in a tube with pistons on either side. Pascal's Principle tells you that if you use the piston on the left side to apply pressure to the water, the water will exert the same pressure on the piston on the right side of the tube. And the pressure is equal to the force divided by the area.

So say you have another tube that's more of a cone shape, with a piston on the left side that has an area of one metre squared and one on the right that has an area of two metres squared. Again, you apply 10,000 Pascals of pressure to the piston on the left side, meaning 10,000 Newtons of force. But the piston on the right side has double the area, so for the pressures to be equal, the water has to apply double the force to the piston as you apply to the water, and so you end up with 20,000 Newtons of force on the right side piston.

This is a huge deal! You're doubling the input force, but you didn't have to put in any extra effort. And the bigger the difference in area, the more extra force you get. To put it in maths terms, the ratio of the output force to the input force is equal to the ratio of the output area to the input area.

Systems like hydraulic lifts take advantage of this by having big differences in area on either side of the fluid. So if you want to apply a lot of force to lift something heavy, for example, hydraulics are the way to go.

Now, if you're gonna be using pressure to do stuff, you're probably gonna want to be able to measure that pressure, which is where manometers and barometers come in. A manometer is just a U-shaped tube with a fluid inside. Say you wanted to use one to measure the pressure of a bike tire. You'd stick one side of the tube in the tire, leaving the other side open to the atmosphere. If there's a difference in the pressure on each side of the manometer, whichever side has the higher pressure will push the fluid away from it, creating a difference in the height of the fluid on either side of the U - in this case, the inside of the bike tire has a much higher pressure than the atmosphere, so the level of the fluid on the side of the U that's closest to the tire will be lower.

If you measured the difference in fluid height directly, you'd get what's known as gauge pressure - the difference between atmospheric pressure and the pressure inside the tire. But the actual pressure of the tire - the absolute pressure - is the atmospheric pressure plus the gauge pressure. So the pressure inside the tire will be equal to the atmospheric pressure plus the density of the fluid inside the manometer times small *g* times the difference in the heights of the fluid.

Barometers, on the other hand, use a long, vertical tube that's closed on one end, usually filled with mercury, and then stuck upside-down in a bowl that's also full of mercury, with the closed end of the tube at the top. The pressure of the atmosphere pushes down on the mercury in the bowl, which keeps a certain amount of mercury in the tube. At standard atmospheric pressure, the mercury in the tube will be exactly 76 centimeters high. If the air pressure goes up, so does the level of mercury, and vice versa.

So we have one more property to talk about when it comes to fluid at rest, and it's the one that supposedly made that guy run naked through the streets yelling, "Eureka!" That guy was Archimedes, and he lived in Greece in the third century B.C.E. Legend has it that he was asked to find a way to figure out if the king's crown was pure gold, and the best way to do that was calculate its density. Archimedes could measure the crown's mass easily enough, but he

didn't know how to find its density. He was taking a bath one day when he realized that the volume of the water displaced by an object is equal to that's object volume. And since he already knew the crown's mass, that meant he'd be able to find its volume, and therefore its density, just by putting it in water. That's when he did the whole running-through-the-streets-naked thing.

So Archimedes discovered that when you put something in a fluid, the fluid's volume increases by the amount of the object's volume. This tells us a lot about what makes objects float or sink.

For example, say you have a tub of water and two balls of the same size but of different densities - say one is an American-style billiard ball and the other is a racquetball. We're going to gently place the balls in the middle of the tub, let go, and explain what happens to them. But first, let's talk about the forces acting on the water that's occupying the space where we're gonna put them.

Picture a sphere of water within the volume of water that's in the tub. What are the forces acting on that watery sphere? Well, the force of gravity is pulling it down, and since the sphere is in static equilibrium, there must be some force pushing up on it, counteracting the force of gravity. We call that force the buoyant force, and it comes from the fact that water pressure at the bottom of the sphere is greater than the pressure at the top.

Now let's put the billiard ball where the sphere of water used to be. What are the forces acting on that? The force of gravity that's pulling down on the billiard ball is stronger than the force that was pulling down on the sphere of water. That's because the billiard ball is denser than water, so even though the ball and the sphere of water have the same size, the ball is much heavier. But the buoyant force on the billiard ball is exactly the same as it was on the sphere of water, since they're the same size and shape. That's Archimedes' Principle.

There's a buoyant force pushing upward on objects in water, and it's equal to the weight of the water that the object displaced. The billiard ball weighs more than the sphere of water that it's replacing, so there's a net downward force on the ball, and it sinks to the bottom of the tub.

But if you were to fill that sphere of water with a racquetball, the opposite would happen. In that case, the force from gravity pulling it downward is weaker than the force pulling down the sphere of water, but the buoyant force pushing upward is still the same. So there's a net force upward on the racquetball, which is why it floats to the top of the tub. Some of the racquetball will pop out of the water, but some of it will stay underwater. In fact, once it stops moving, the racquetball will displace a volume of water that weighs exactly as much as the ball, because at that point, the buoyant force pushing the racquetball upward and the force of gravity pulling the racquetball downward have the same magnitude, so they cancel each other out.

Thanks to Archimedes, we know why objects float and sink!

Today, you learned about the properties of fluid at rest, including density and pressure. We also talked about Pascal's Principle, and how it's used in hydraulics. Then we covered how manometers and barometers measure pressure, and finally, we explained Archimedes' Principle and the buoyant force.

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