Fluids in Motion: Crash Course Physics #15

Crash Course: Physics
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You know what can be kind of peculiar and surprising? The fact that whenever you want to shoot outside everyone decides to mow their lawn.

You know what else can be kind of peculiar and surprising? Water. And in the right circumstances, I could even take water that's flowing down and spurt it straight up. How?

All of these things are possible thanks to the study of the flow of fluids, known as Fluid Dynamics.

Theme Music

By now, you've picked up on the fact that, even though we live in the physical universe, describing the rules of the universe sometimes requires us to pretend that certain things aren't happening.

Like the time we rolled a bunch of stuff down a ramp and pretended that there was no kinetic friction. The same is true when we talk about fluids. Because fluids in motion are dynamic and there are many, many things going on in and around them all at once.

So, in order to grasp the essentials of fluid dynamics, let's just do some pretending, shall we?

For one thing, we're going to consider the fluids in our examples to be incompressible - meaning that their densities won't change. We're also going to assume that fluids flow perfectly smoothly and have no viscosity.

You've probably heard of viscosity before. When a fluid flows easily like water, we say that is has a low viscosity. Fluids that don't flow as easily, like honey, have a higher viscosity. And much like kinetic friction does in moving objects, viscosity tends to complicate things in moving liquids. Which is why we're generally going to pretend that the fluids we're studying don't have any.

Now, say you have some water - which exists under all these hypothetical conditions in a pipe moving along smoothly. This pipe narrows about halfway through so that one end is more narrow than the other. This shape is going to effect some properties of the water's flow as it passes through the more narrow side of the pipe as compared to the wider side.

But one thing that won't change is the mass of water that's moving through any given area in the pipe over time. This is called the mass flow rate, and it's always going to be the same everywhere in the pipe. That's just because, as water flows through the pipe, it pushed along the water in the rest of the pipe, too.

So, if one part of the pipe has, say, a kilogram of water moving through it every second, the rest of the pipe also has to have a kilogram of water moving through it every second.

This fact, that the mass flow rate at one point in the pipe will be equal to the mass flow rate at any other point, is called the equation of continuity. And it can tell you a lot about the relationship between the velocity of a fluid and the cross sectional area of the pipe that it's flowing through.

Let's say you're an engineer for the Water Department of Hypothetical City and you need to understand the mass flow rate of hypothetical water that's going through a certain point in your underground pipe system. But, you don't know that mass that's going through that part of the pipe at any given moment. All you do know are the water's velocity and the area of the cross section of that certain section of pipe.

In order describe the mass flow rate, you'll have to use what we know about density, area, and velocity to work out some algebra magic.

First, let's have a look at a cross section of that point of the pipe.

From our last lesson, you know that the mass of the fluid moving past this cross sectional area over time is equal to its density times its volume. And the volume of the fluid moving past this point is simply the area of the pipe at this cross section times the distance the fluid moves. And from our episodes on the physics of motion, you also know that the distance the fluid moves divided by the change in time is equal to the fluid's velocity.

So, by putting all that together, you can get a different version of the equation of continuity.

At any given point in the pipe, the density of the fluid flowing through it time the area of the pipe, times the fluid's velocity, will be the same as for any other point in the pipe.

And since you're dealing with an incompressible fluid, the density is going to be the same for every point in the pipe anyways. So, really, you've just figured out that at any point in the pipe, the area of the pipe times the fluid's velocity will be the same as for any other point.

It's the same thing we said before. The mass flow rate is the same for every point in the pipe. But instead of putting that relationship in terms of mass and time, you're putting it in terms of area and velocity.

And in your role as water-department engineer, this is important for you to know. Because it means that where the pipe is narrower the fluid will have to flow faster in order to compensate.

But here's the weird thing. A fluid that's flowing really fast actually has less pressure than when it's flowing more slowly. Sure, it might feel like it's exerting more force than when it flows through a wider opening, but that's not what physicists mean when the talk about the pressure in a pipe. They're really talking about the pressure on the walls of the pipe.

This means that the slower the fluid flows, the more pressure it puts on the pipe itself. This is known as Bernoulli's principle.

It states that, "The higher a fluid's velocity is through a pipe, the lower the pressure on the pipe's walls, and vice versa."

Bernoulli also came up with what we now know as Bernoulli's equation.

It might look kind of intimidating at first, but when you break it down, it's actually just a way of combining a bunch of things that you've already learned.

Bernoulli based his equation on the concept of conservation of energy. As a fluid flows through a pipe, it won't gain or lose any energy. This means that, no matter where the fluid is in the pipe, if you take all of the forms of energy that the fluid has at that point and add them up, they'll equal the same number as any other point in the pipe.

To better understand this, have a look at how the three forms of energy in a fluid are represented in Bernoulli's equation.

First, there's pressure times volume.

In our episode on work and energy, we defined energy as the ability

to do work. And when a fluid applies pressure and moves the volume of fluid that's downstream, it's doing work. So, pressure times volume must be a form of energy.

The first term in Bernoulli's equation takes that energy and divides it by volume, which just leaves pressure. Next, a flowing fluid also has kinetic energy. When we first talked about kinetic energy, we said that it's equal to half of an object's mass times its velocity squared. Again, Bernoulli divided this form of energy by volume to get half the fluid's density times its velocity squared. That's called the kinetic energy density, and it's the second term of Bernoulli's equation. Finally, a flowing fluid also has the potential energy that comes from gravity, and we've said before that the potential energy from gravity is equal to an object's mass times small g, times its height. When Bernoulli divided that by volume, he got density times small g times height. The potential energy density and the third term of his equation.

Why divide all these terms by volume? Well, when it comes to fluids, it's just easier to talk about things in terms of density than it is to talk about mass. So when you look at his equation piece by piece, you can see that Bernoulli was really just putting conservation of energy into a special form that would be useful for fluids. Now let's look at a special case of Bernoulli's equation known as Torricelli's Theorem.

Torrecelli's Theorem uses conservation of energy to find the velocity of fluid flowing from a small spout in a container, and it says that the velocity of the fluids coming out of the spout is the same as the velocity of a single droplet of fluid that falls from the height of the surface of the fluid in the container. In other words, the pressure that's pushing the fluid out of the spout gives it the same velocity that it would get from the force of gravity. To see this theorem in action, let's say you're not a water department engineer, you're just you. And you're watering your garden with the water you've saved up in your rain barrel. Your barrel doesn't have a top, and you're watering your carrots and lettuce and stuff from a hole or a spout in the side. Now, you want to know what the velocity is of the water coming out of your spout. From Bernoulli's equation, we know that the sum of the pressure, kinetic energy density, and the potential energy density of the water at the top of the barrel will equal the sum of those three qualities of the water coming out of the spout. But we can simplify that relationship a bit to find the velocity of the fluid coming out.

First, the upper surface of the water in the barrel and the water that's coming out of the spout are both exposed to the atmosphere, so the pressure at those points would be the same, it's just atmospheric pressure. So we can cross off the pressure from each side of the equation. Now there might be water coming out of the spout, but the top of the barrel has a much bigger area, so the water at the top of the barrel isn't going to be moving much. In fact, we can say that its velocity is basically zero, which means that the kinetic energy density for the water at the top of the barrel is zero. Finally, we can cross out the density in each term of the equation, since it's not changing. We're left with a much simpler equation with only three terms, an equation that should look very familiar if you've watched our episodes on the physics of motion.

It's the kinematic equation! You already know the two main kinematic equations, the definition of acceleration and the displacement curve, and you can rearrange them to get another equation that relates to displacement, velocity, and acceleration, without considering time. It's exactly the same equation as the one we just found by using Bernoulli's equation to describe the velocity of water coming out of the spout.

So Torricelli's theorem tells you that if a droplet of water fell from the same height as the top of the barrel, when it reached the level of the spout, it'd have the same velocity as the water coming out of the spout. Now you know how fast the water's coming out of your rain barrel and how much water you're putting in your garden over a certain amount of time. But you wanna try something fun? Let's turn the spout on your barrel so it's pointing up instead of down. If the water from the spout could shoot straight up, the stream would get exactly as high as the water at the top of the barrel before falling down to the ground.

Today, you learned about fluids in motion with a focus on the continuity equation, Bernoulli's equation, and Torricelli's Theorem. You also learned that lawn mowers are loud.

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