Fluid Mechanics and Its Applications
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Lecture 1A
What is a fluid?

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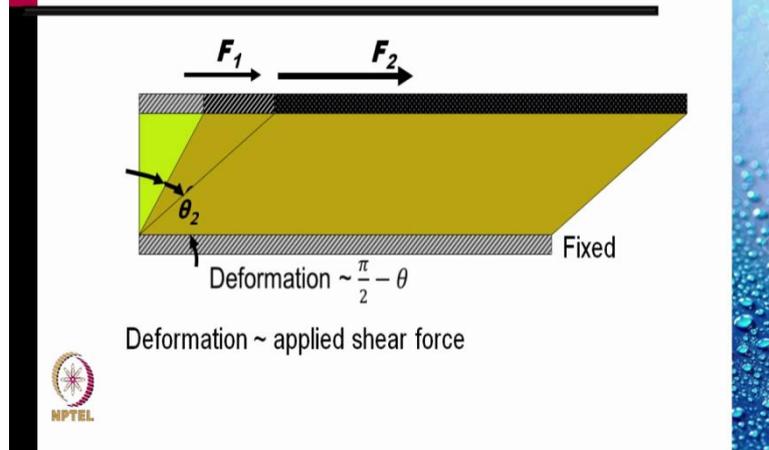
What is a fluid? A fluid is something that flows. What does flowing mean? Let us take this example. The two flat plates shown hatched in between which there is a green substance. The lower plate is fixed. On the upper plate we apply a force F_1. If the green substance was a solid, then the upper plate would move under the action of force, and will come to a stop after a while. The green substance now has been shown in a brown color, and the angle from 90 degrees has reduced to an angle theta1, less than 90 degrees.

What does it mean? That there is no more motion of the upper plate when the force F1 is applied: that force F_1 must have been overcome by some internal force produced within the solid. This internal force is the shear force. If we applied a larger force F_2, then the plate will again come to rest, but with more distortion. Now the angle will reduce to θ_2. That means that when we deform a solid in shear, a force builds up to oppose the deformation, and that force depends upon the deformation: more the defamation the more is the force. In the earlier case, the opposing force is F_1, now the opposing force is F_2 with more deformation. So, more the defamation more is the opposing force.

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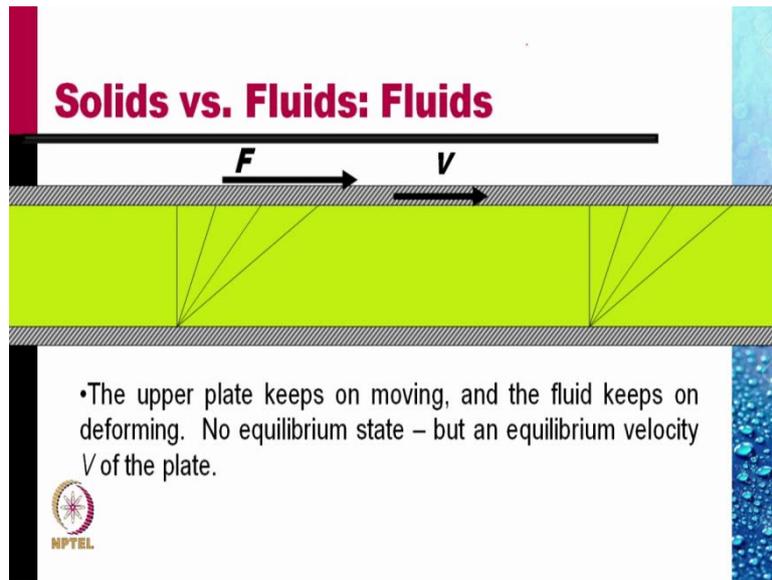
Now, if the substance was not a solid, but a fluid: I marked two lines. When you apply a force F, the upper plate never stops, it keeps on moving. It accelerates first, 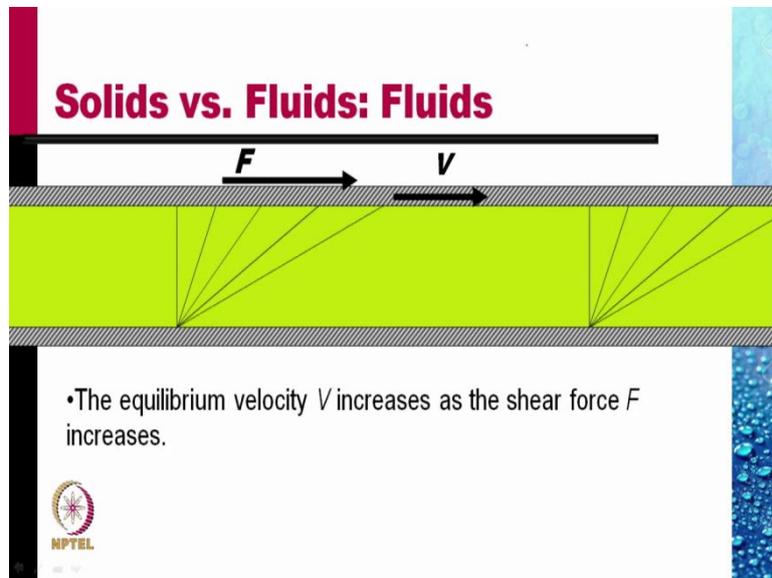but ultimately acquires a constant velocity V. What does that mean? The upper plate keeps moving and the fluid keeps on deforming. No equilibrium state, but an equilibrium velocity V of the plate.
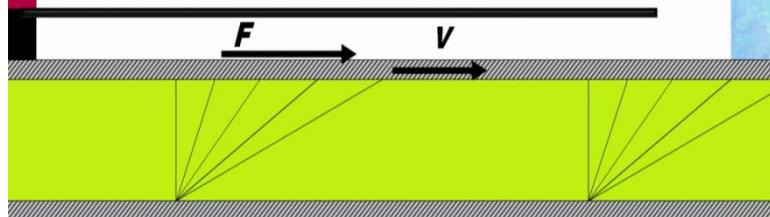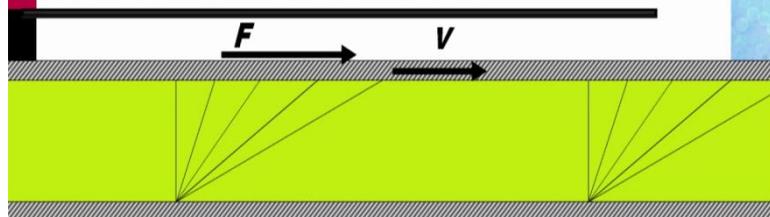
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Solids vs. Fluids: Fluids

•This means that mere deformation of fluid does not build up resisting forces.

Solids vs. Fluids: Fluids

•Since there is an equilibrium velocity (more the velocity larger the force), a resisting force is developing for sure.

• The resisting force is, thus, dependent not on *deformation*, but on *deformation rates*.

The equilibrium velocity V increases as the shear force F increases. This means that mere deformation of fluid does not build up resisting forces. Since there is an equilibrium velocity, more the velocity, larger the force: a resisting force is developing for sure. The resisting force is, thus, dependent, not on the deformation, but on the rate of deformation.
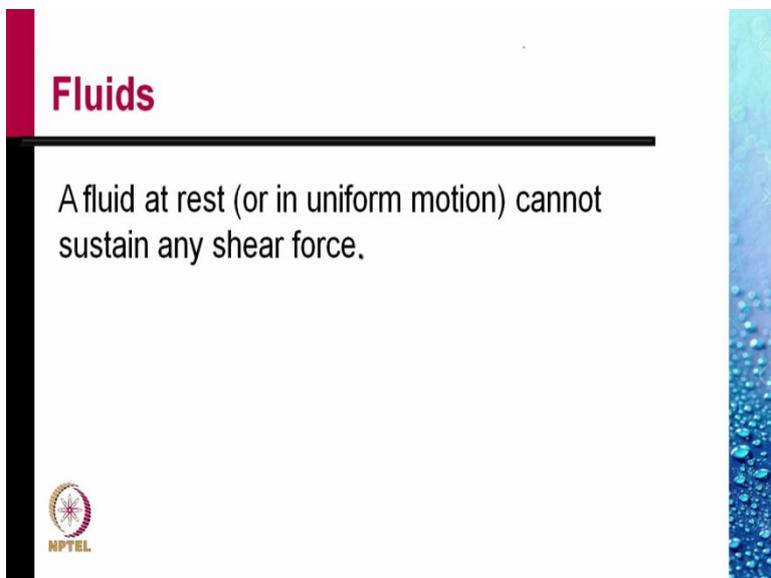
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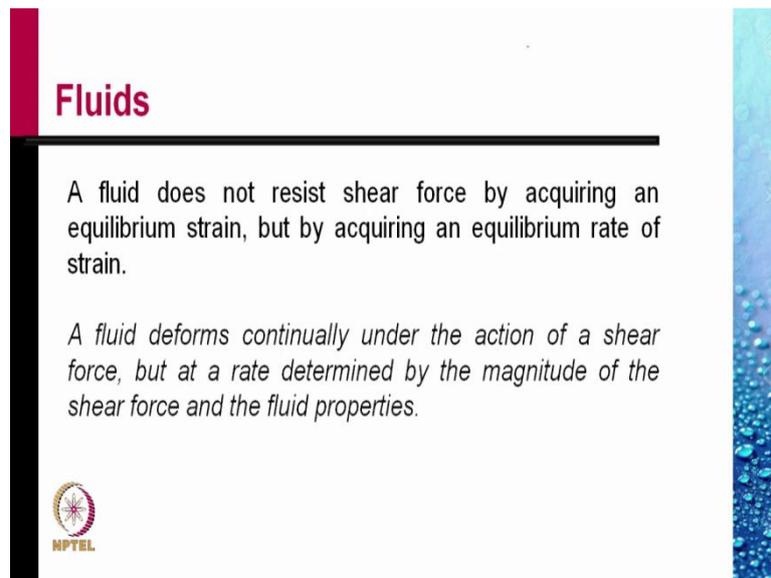
A fluid does not resist shear force by acquiring an equilibrium strain. We define a fluid thus: a fluid deforms continually under the action of a shear force, but at a rate determined by the magnitude of the shear force and the fluid properties.

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A fluid at rest (or in uniform motion when there is no deformation) cannot sustain any shear force. This we use as the defining statement of a fluid or as a definition of a fluid: a fluid at rest or in uniform motion cannot sustain any shear force. A relative motion of fluid is necessary to develop any shear force.
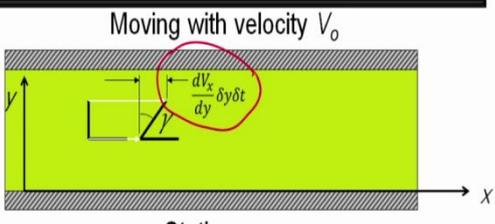
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When a fluid is in motion, there may exist shear forces as well. Let us consider the rate of deformation. Again, we have the same setup as before. We have a green fluid. On the green fluid we have marked two lines at right angle to each other, one a horizontal line segment, and the other a vertical line segment.

This fluid is moving. Later on we will know that the fluids have a property with which you say that there is no slip between the fluid and the nearby wall. So, fluid at the stationary plate would have zero velocity. It would be stationary and fluid adjacent to the moving plate would be moving with a velocity V_o, the velocity of the plate itself. And the higher we go more is the velocity; lower the velocity is lower.

So, after a time δt, upper end of the vertical line moves through a larger distance than does the lower end of the vertical line, so that the location or those two black lines would now be this. So, the angle between these two lines has now decreased. What is the decrease in this angle? This decrease is γ, called the shear deformation. And you would see by simple Taylor series expansion that this would be given by $\frac{dV_x}{dy} \delta y \times \delta t$.

So, this is the additional distance that the upper end of the vertical line moves over the distance moved by the lower end of the vertical line. So, the angle γ, which is the deformation in time δt is $\frac{dV_x}{dy} \delta t$. So, deformation in unit time, or the rate of deformation is $\frac{dV_x}{dy}$.

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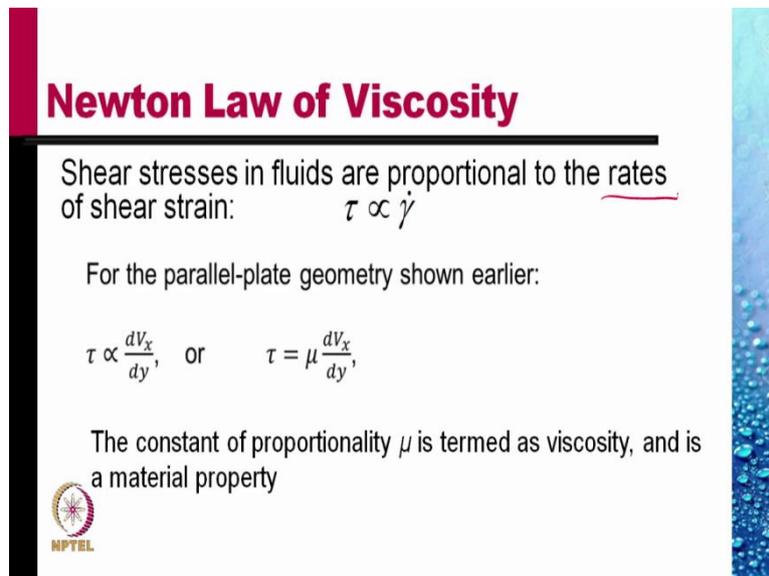
There is a famous law of viscosity, the Newton law viscosity, which you must have done in your high school, which states that shear stresses in fluids are proportional to the rates of shear strain: the rates of shear strain, not the shear strain itself, but the rates of shear strain. So, that τ is proportional to $\dot{\gamma}$, the dot representing the differentiation with respect to time: $d\gamma/dt$. And we have just shown that $\dot{\gamma}$, the rate of deformation (shear deformation), the rate of shear strain is $\frac{dV_x}{dy}$ in the case discussed.

So, for the parallel plate geometry shown earlier, τ, the shear stress is proportional to $\frac{dV_x}{dy}$ or introducing the proportionality constant μ, shear stress is equal to $\mu \frac{dV_x}{dy}$. The proportionality

constant is termed as the viscosity and is a material property. Now, this is a very famous relation, but the applicability of this is not universal. In fact, there are whole classes of fluids which do not obey this law.

So, the fluids that obey this law are called Newtonian fluids. Newtonian fluids are those fluids which obey the Newton law of viscosity with a constant μ. On the other hands, the fluids which do not obey this law are termed as non-Newtonian fluids

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We can look at the dimensions of viscosity, since τ is equal to $\mu \frac{dV_x}{dy}$. So, dimensions of viscosity would be dimensions of shear stress divided by the dimensions of V/y. The dimension of viscosity are force divided by L^2, and we get the dimension of μ in MLT system as $ML^{-1}T^{-1}$. The units are correspondingly kilogram per meter second, which also is Pascal-second, which is derived from this. This is s and FL^{-2} is Pascal. So, Pascal-second.

The other unit is Poise. Poise is a unit which is equal to 10^{-1}, or 0.1 Pa-s. The most commonly used units in fluid mechanics is centipoise which is one-hundredth of a poise, which is equal to 10^{-3}, or milli-Pa-s And why is that used? Because viscosity of water at room temperature is about 1 centipoise. Something easy to remember, and centipoise is10^{-3} Pa-s. Pa-s is the SI unit, which you would be using in all your problems that you do in a course in fluid mechanics. But in quite a bit of engineering literature, the viscosity is given in centipoise.

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There is a wide variation of the values of viscosity. Air has a viscosity of 0.0185 centipoise, for gasoline it is 0.29 centipoise, for water as we just said it is 1 centipoise. Mercury is a little more viscous at 1.55 centipoise, and the SAE 30 motor oil that you use in your cars typically is 440 times the viscosity of water, or 440 centipoise: very viscous. Gasoline is also a very viscous substance.

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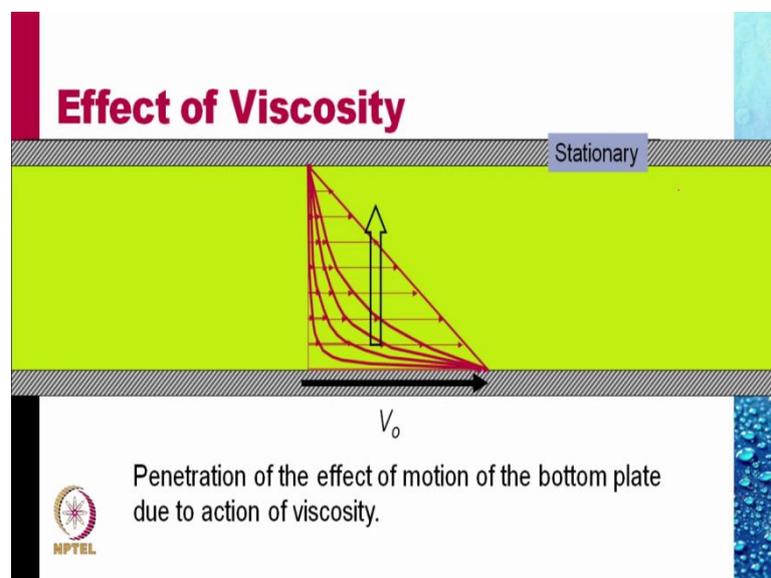
Effect of viscosity: what does viscosity do? Again, we have a similar geometry: two parallel plates with a fluid in between. But in this case, we have the upper plate stationary and the lower plate suddenly start moving at a velocity V_o. Initially all this fluid was stationary. The

lower plate is set into motion with an impulsive velocity V_o, that is it is suddenly given a velocity V_o.

So, what will happen? Because of the no slip condition that was discussed just a little while ago, the fluid in the immediate contact with the lower plate starts moving immediately with a velocity V_o. The fluid adjacent to it is still stationary. So, this gives a velocity gradient, which is negative of course. The velocity is decreasing in the upper direction. And so that creates a shear stress. Because of this shear stress, the fluid adjacent to this adjacent fluid starts moving slightly.

And after a little time, you might get a velocity profile which looks like this. This reddish line shows you the variation of velocity in the vertical direction across the fluid after a little time δt, a time after the lower plate has been set into motion. You see that the fluid in the upper layers has not moved at all.

Now, this has set up the velocity gradients again, so, there would be more shear stresses, and because of which the effect of the lower plate motion will penetrate upwards, and after a little more time, we might get a velocity profile like this; and then like this; and then like this. After a long time we would get a velocity profile which would be straight. We will see later on in the course, that mathematically, we will obtain a straight line profile between the plates.

This is the profile that you used in your high school between two parallel plates. You call this flow, a Couette flow, a steady state flow after long time. What is happening? The effect of the motion of the lower plate is diffusing upward. Diffusion is the word. We say the momentum (later on we will use another word vorticity) is diffusing upwards. Penetration of the effect of motion of the bottom plate due to action of viscosity penetrates upwards. This is the effect of viscosity.

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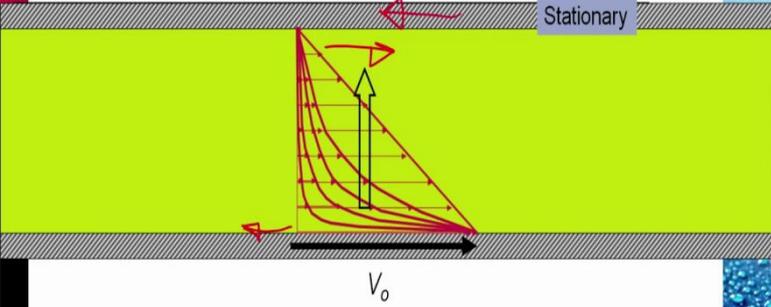The penetration increases with time. Action of viscosity is like a process of diffusion. The viscous actions of fluid resist the motion of the lower plate. At the steady-state, the fluid attempts to drag the upper plate to the right. There would be shear stress or the lower plate in that direction. So, we need to apply a force constantly on the lower plate to keep it moving. Not only this, this fluid would apply a shear force in that direction on the upper plate: on the upper plate.

So, we will need to apply a force on the upper plate in the opposite direction to keep it stationary to overcome this effect of drag on the upper plate. We will have occasion to calculate these forces and discuss more later on in the course.
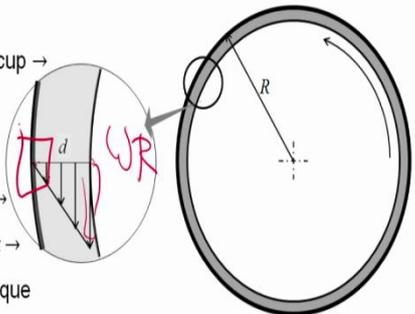
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A rudimentary viscometer: How do we measure viscosity? We have two drums, an inner drum and an outer drum (or cups). Here I am showing the top view of the two cups. There is a fluid in between the two cups. The inner cup is rotating because of the viscous action. There would be a force that would develop on the inner cup, which we will need to apply to keep it moving, or a force that we need to apply on the outer cup to keep it from rotating. We measure that force. The picture between the two cylinders (two cups) looks like this.

The velocity there is ωR. The gap is d. The velocity on the stationary cup is zero. So, we assume linear velocity in the gap. We calculate the velocity gradient. From velocity gradient we find out the shear stress by applying the Newton's law. Then you find the force on a small element like this. We find the torque on the small element by multiplying by R, the radius, and then integrate to find out the total torque that we need to apply to keep the outer cup from moving.

We can measure this and relate it to mu and that is how the viscosity is calculated using this rudimentary viscometer. We will do this problem later on in the course. I have included here just to give you a flavor of what kinds of calculations are involved. Probably you have done this problem in your high school as well.
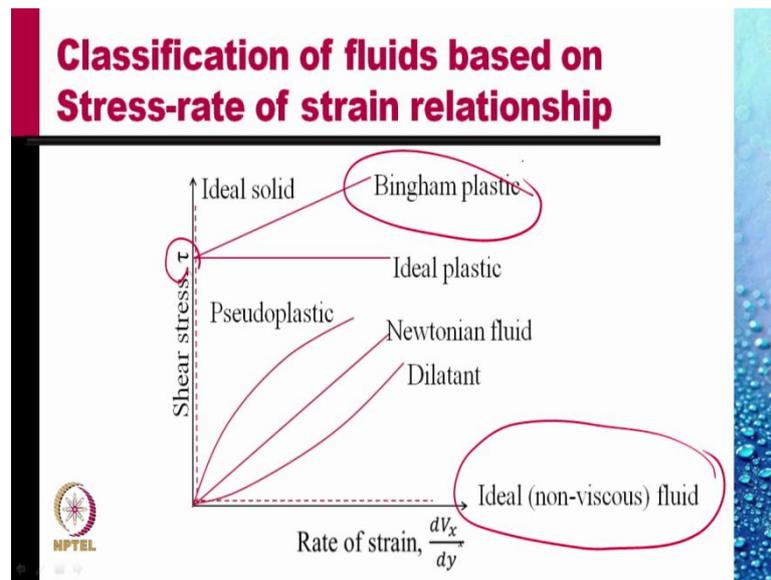
Classification of fluids based on stress-strain relationship: You see in the solid, there is no rate of strain, just strain and we have a shear force. For an ideal fluid, non-viscous, the viscosity is 0. We can have any shear-rate or stain and there will be no shear stress. For a fluid that we discussed (a Newtonian fluid), there is a linear relationship. The value of μ is constant, shear stress is μ times the rate of strain.

But there are other kinds of fluids. a pseudo-plastic or a dilatant, in which this is not a straight line. These are all non-Newtonian fluids. Or we may have a plastic in which up to a given level of shear stress, there is no rate of shear strain, but then you can develop any rate of shear strain after that, for the same stress. We have fluids that have a threshold and beyond that you need more shear-stress to get a rate of strain. These are known as Bingham plastics. In this course, we would largely, or we would essentially, discuss Newtonian fluids only, Within this lecture I will give you some examples of Bingham plastics.

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You see, a rod is rotating in a fluid. You can see these two pictures. these are .gif's. The fluid is rising up the road. And when a big blob is formed, it collapses down and starts climbing again. In a Newtonian fluid, inertia would dominate and the fluid would move to the edge of the container away from the rod: centrifugal action. But however, the elastic force generated by the rotation of the rod and the consequent stretching of the polymer chains in the solution that we are using here results in a positive normal force, force upward. The fluid rises up the rod. The bulbous shape remaining at the end of the video is the onset of instability as the mass that has been forced up the rod relaxes, and overcomes the force pushing it from below. The rod climbing effect.

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Another non-Newtonian effect is the die swell. You see, if a Newtonian fluid was flowing down a die or flowing down a hole, it would follow a contour like this. It will accelerate and because of acceleration, the cross section will decrease, because the volume flow rates at any two cross-sections are the same.

So, if the fluid is accelerating downwards, then downwards the cross-sectional area would have been small. But you use polymers like a two-percent aqueous solution of polyacrylamide. The fluid swells after coming out. Fluid swells means is velocity is decreased because of being pulled up by a normal force. There is a third non-Newtonian effect that I want to show you.

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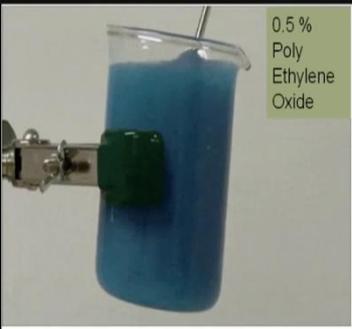
And this is very interesting and open siphon. Again, this is because of this non-Newtonian effect. Polyethylene oxide, a 0.5 percent solution of polyethylene oxide, a polymer. You start the flow and because of tension because in the fluid, the beaker empties itself.

That brings us to the end of this lecture. In the next presentation, we will discuss fluid flow phenomena.

Thank you.