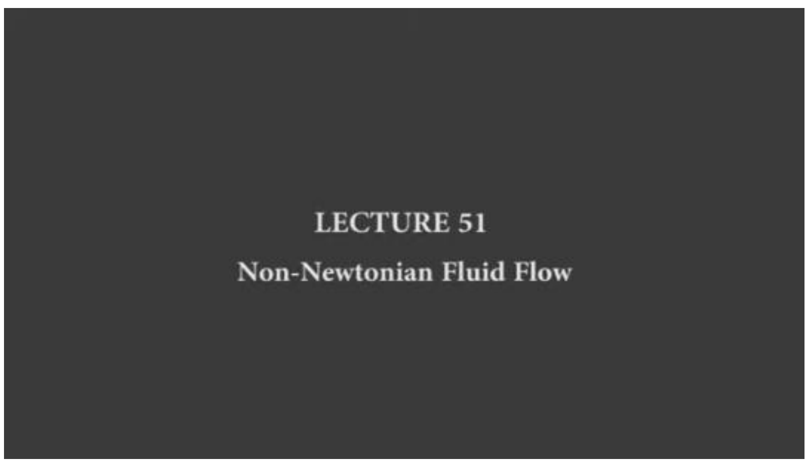
IMPACT OF FLOW OF FLUIDS IN FOOD PROCESSING AND PRESERVATION

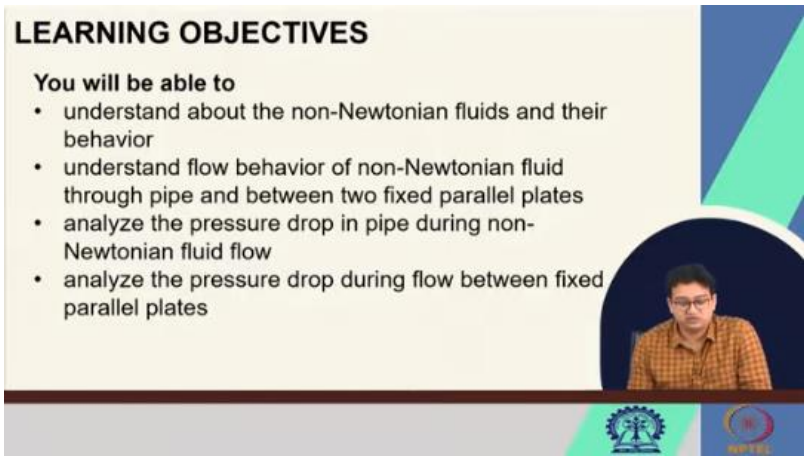
Lecture51

LECTURE 51 : Non-Newtonian Fluid Flow

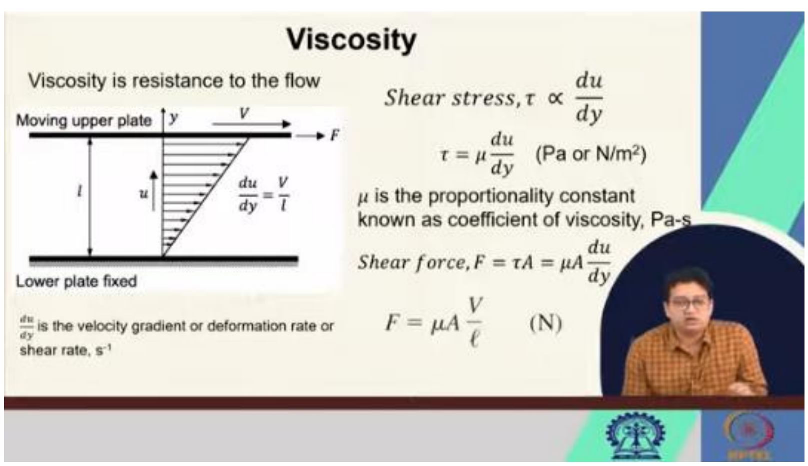
Hello friends, today we will be looking at the next topic under the generic topic of the impact of flow of fluids in food processing and preservation. So, this is week 11, and we will mainly be focusing on non-Newtonian fluid flow. So far, you have looked at Newtonian fluid flow through different geometries, such as pipes and between fixed parallel plates. From now on, we will mainly focus on the flow of fluids that are non-Newtonian in nature. Once you cover this topic, you will be able to understand non-Newtonian fluids and their behavior.



Then, you will be able to visualize and understand the flow behavior of non-Newtonian fluids through pipes and between two fixed parallel plates. There are many scenarios where fluid may flow through different geometries, but we will mainly focus on fluid flow through pipes and between two fixed parallel plates. After that, you will be able to analyze the pressure drop. in pipes during non-Newtonian fluid flow. We will look at how to derive the pressure drop equation when non-Newtonian fluid flows through a pipe. Finally, when non-Newtonian fluid flows between two parallel plates, we will see how to derive the pressure drop equation.

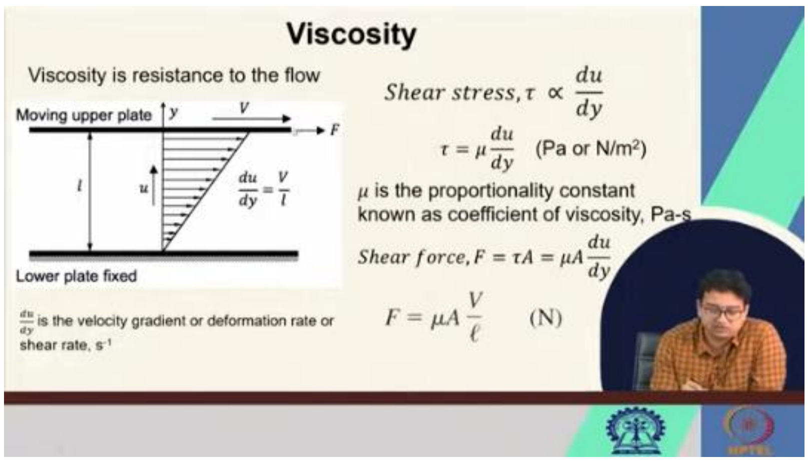


Now, a little bit of recapitulation. I know you have already learned about this. Since we are talking about the flow of fluids, we must know about the property of the fluid, which is viscosity—a very important parameter. Viscosity is nothing but the resistance to flow. When fluid tries to flow over a surface or through any geometric structure.



So, ah the there will be some resistance acting on that ok. So, the resistance will simply ah the resist the flow of the fluid through the any structure. So, that is the property is known as the viscosity. Now, here if you look at this picture. So, in the picture it is a very familiar picture.

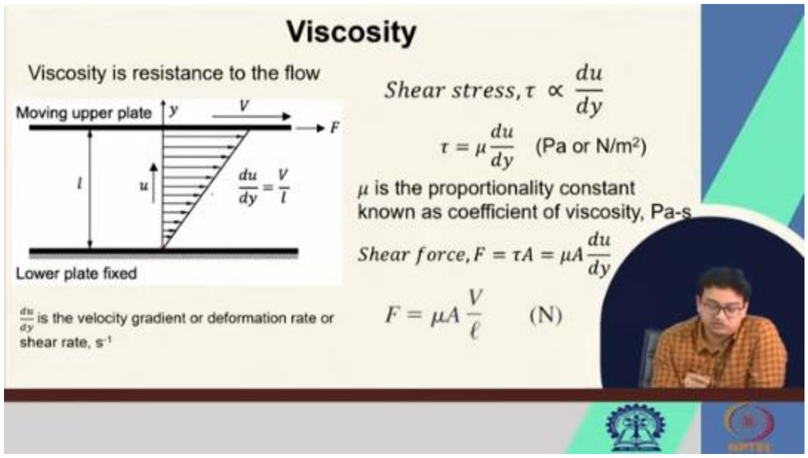
So, if you look at so, this is the. So, here we have a top plate that is actually moving and we have a bottom plate that is lower plate which is fixed. And, in between this plate we have a fluid. Now, the top plate or the upper plates is being dragged with a constant force with this capital F and it has got the velocity of capital V. Now, you see ah that fluid that is just adjacent to the next to the internal part of that ah the top plate here that is at the complete stop that is called actually no slip condition.



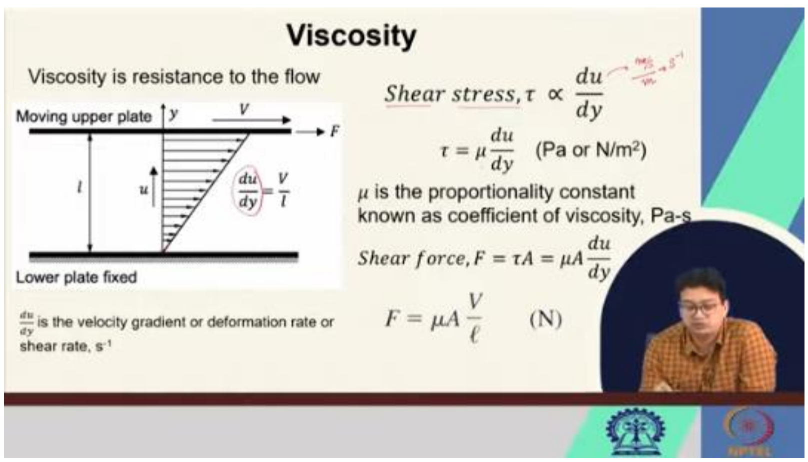
So, the fluid that is touching the surface of the plate internal part of the plate of the top part ok that is actually coming to the ah stop when it is not moving ok. Now, when it is being dragged So, the top part will also be being dragged with the plate ok. Now, because of the friction between the layers the in so, the adjacent layer also will be dragged, but the velocity of this layer will be somewhat less ok that is because of the viscosity and like that way there will be a development of the velocity profile over the across the gap between the plates.

Here, if you look at over here in this place, the lower plate is not moving at all. So, it is at complete rest. So, at this point, the fluid is at complete stop. Here, the velocity is 0. So, you can see that here we are having the velocity gradient.

So, velocity gradient, if we write in the differential form, that is actually du by dy, that is equals to V by L, capital V by L. Now, the shear stress so, look at over here. So, this is being dragged and the stress is acting on the surface. So, the shear stress over here it is denoted by the tau it is proportional to the velocity gradient. So, this is also known at the known as the deformation rate or shear rate and it has the unit of per second.

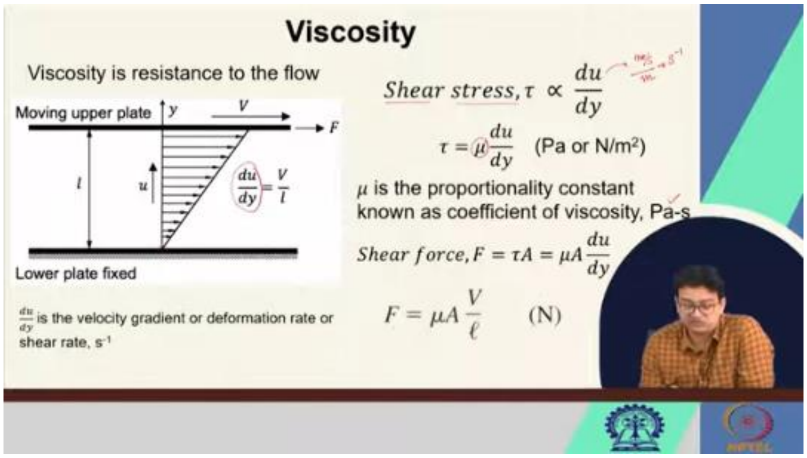


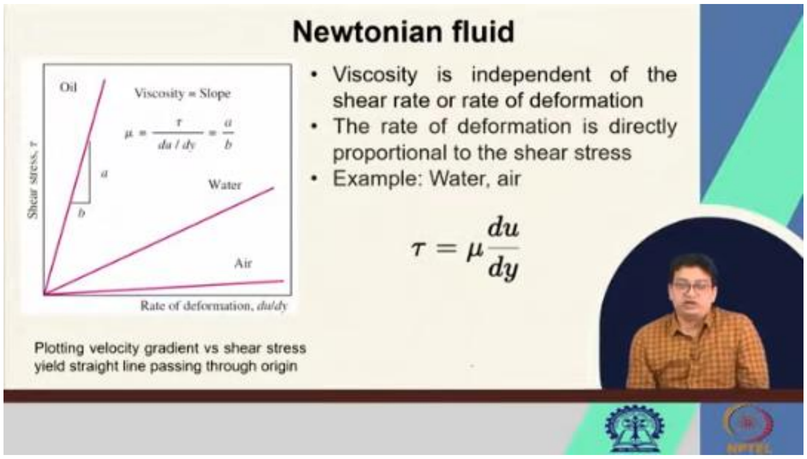
So, the du part is the the velocity meter per second here it is by beta. So, it gives a, this one gives per second ok. Now, when you will opt out for the proportionality part. So, you have to put a proportionality constant that is coming over here is a mu.



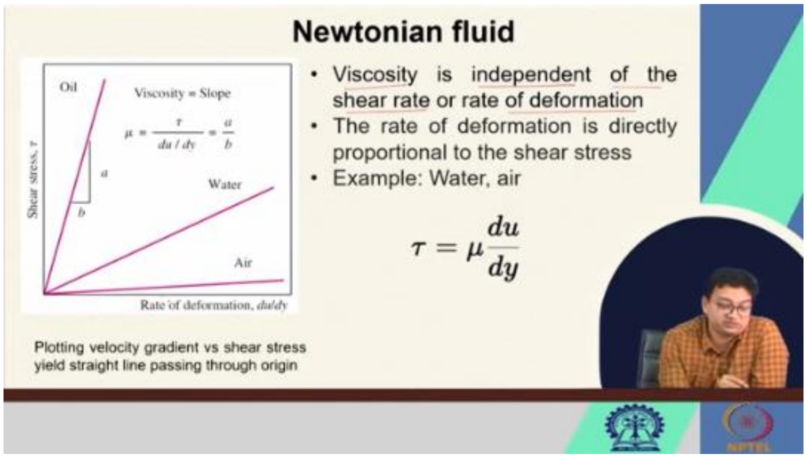
So, tau equals mu multiplied by du/dy. So, the shear stress has the unit of Pascal, Newton per meter square. So, this is a very basic idea I am giving. So, where mu is known as the proportionality constant or also as the coefficient of viscosity, it has the unit of Pascal second. So, shear force is nothing but the stress multiplied by an area.

So, this is the area of the plate that is touching the fluid surface. So, let us say this area is capital A, that is equal to mu A multiplied by du/dy. So, this is actually called Newton's law of viscosity. So, F equals mu A V by L. Now, based on the viscosity or the property of the fluids, the fluids are classified into two major categories. So, one is the Newtonian fluid, and another one is the non-Newtonian fluid.

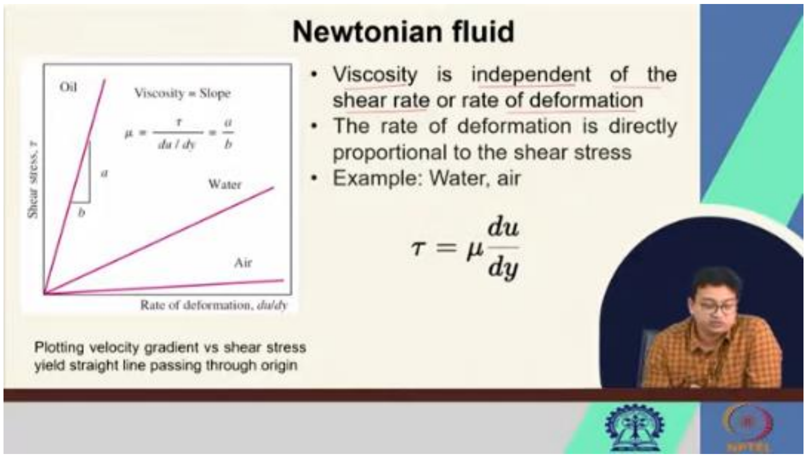




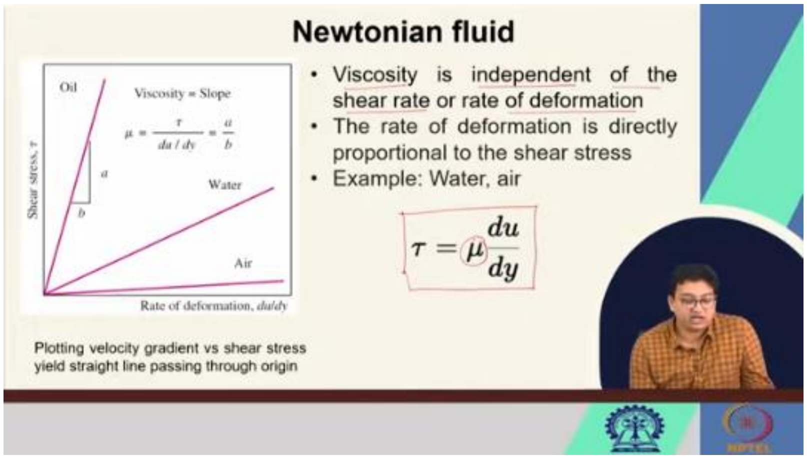
Perhaps you already have an idea of the Newtonian fluid, and of course, of the non-Newtonian fluid, but just to give you a very basic idea. Newtonian fluid obeys Newton's law of viscosity. So, viscosity in this case is independent of the shear rate or rate of deformation. So, that means if you look at this picture over here. So, on the y-axis, we have shear stress.



It is the tau, and here we have the rate of deformation that is denoted by du by dy. So, if you plot the rate of deformation with the shear stress, you will get a linear relationship that actually passes through the origin. So, viscosity is independent of the shear rate and rate of deformation, and the rate of deformation is directly proportional to the shear stress. So, that means, if you—and also in the Newtonian fluid—the viscosity is not dependent on time, okay.



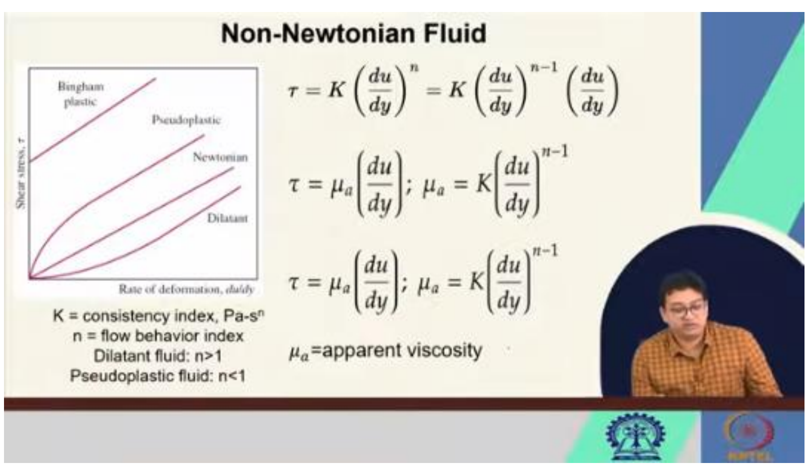
So, here the example is water or air. So, many of the foods actually behave like a Newtonian in nature, and here we have the main equation: tau equals mu multiplied by du/dy, where du/dy is the rate of deformation and mu is the viscosity. So, this is the very basic idea of the Newtonian fluid. Now, coming to the non-Newtonian fluid. So, non-Newtonian fluid does not obey Newton's law of viscosity, okay.



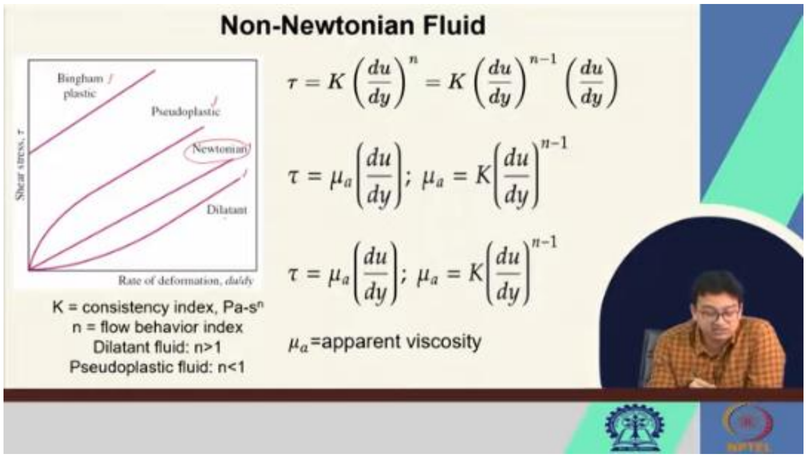
Viscosity also changes with stress or time, okay. So, if the stress keeps on changing and time is changing over the period, the viscosity will also change. Okay. And also, the plot of velocity gradient versus shear stress does not necessarily give us a straight line. It may have a different type of nature, different kind of characteristics.

So, here you can see different kinds of food products. So, ketchup, peanut butter, ice cream, toothpaste, chocolate syrup, mayonnaise. So, they are all actually non-Newtonian in nature. So, ketchup, peanut butter—they have different categories under non-Newtonian fluids.

Ice cream, chocolate at room temperature is solid, but it is also considered non-Newtonian in nature. We have toothpaste, and we also have other products like juices, different kinds of emulsions, and foams—they are all non-Newtonian in nature. Coming to the next part in non-Newtonian fluids: how the equation is expressed, and how the relationship between viscosity and shear stress looks like, okay? Now, in the picture, let us look at it first. So, the rate of deformation versus shear stress shows a different pattern.



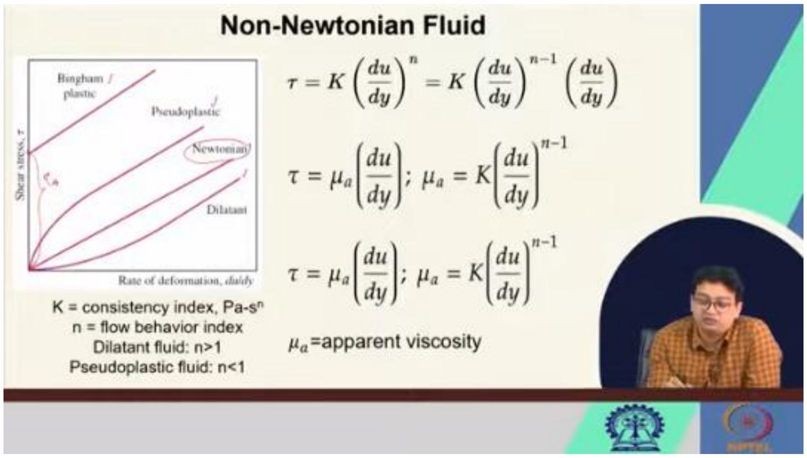
So, this one is Newtonian in nature. So, this one is linear and passes through the origin. Whereas, you can see over here some others are also present. This one is called dilatant pseudoplastic, and over here, this is Bingham plastic. These are all non-Newtonian in nature, and if you look at them, they are not linear—though they pass through the origin, they have different shapes.



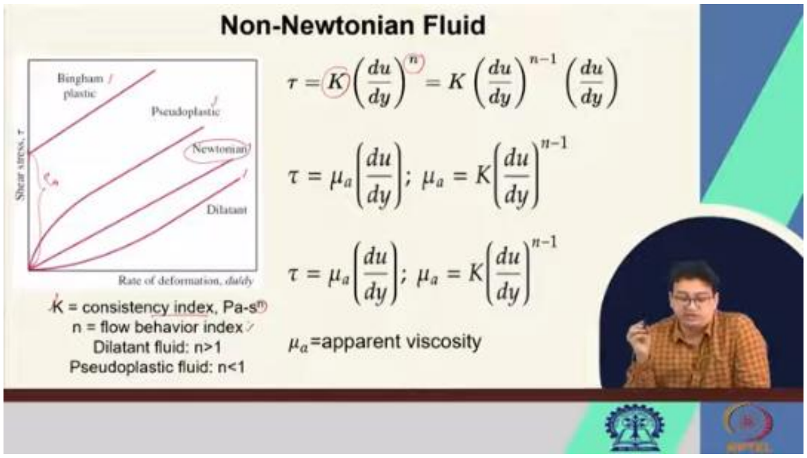
Ok. Bingham plastic, if we look into detail. Bingham plastic, you see, it is starting from some intercept over here in the shear stress. That means some initial amount of force is required to make it flow or to make it deform, ok.

So, this is actually tau naught, you can say, ok. So, we have to apply some initial force to make it flow, like toothpaste. So, if you have toothpaste in a tube, you have to press it really hard to make it come out of the tube. So, that is actually Bingham plastic in nature. Now, the way it is expressed is tau equals K multiplied by du divided by dy to the power n. So, it follows the

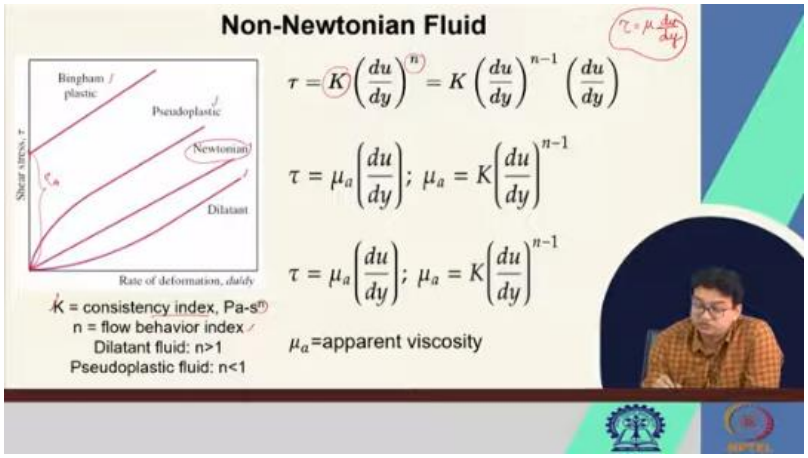
power law profile. So, where K is the consistency index, the unit is Pascal multiplied by s to the power n. So, what is n? n is the flow behaviour index. Now, what does the consistency index indicate? So, consistency indicates it is actually the average measure of the viscosity of the non-Newtonian fluid, ok, whereas flow behaviour index



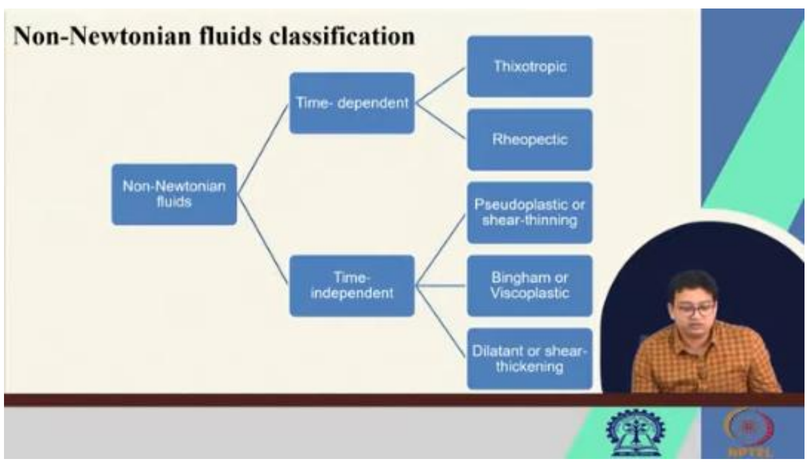
it differentiates the non-Newtonian fluid from the Newtonian fluid and also it indicates the degree of non-Newtonian fluid ok. Now, if you rearrange this one this expression K multiplied by du / dy whole to the power n. So, we are writing it as a K multiplied by du dy to the power n minus 1 multiplied by du / dy. So, we are so, we had you remember we had a relationship of like this ok. So, we are trying to get in this form all right.



So, now, what we can write? So, this part is written as the mu A that is known as the apparent viscosity mu A is the apparent viscosity then finally, if you put mu A over here we will have the form of tau equals to mu A multiplied by du by dy ok. So, we are having this form now in this mu instead of mu we are having mu apparent apparent viscosity So, why it is apparent viscosity? Because it is dependent on the shear stress and also rate of deformation.

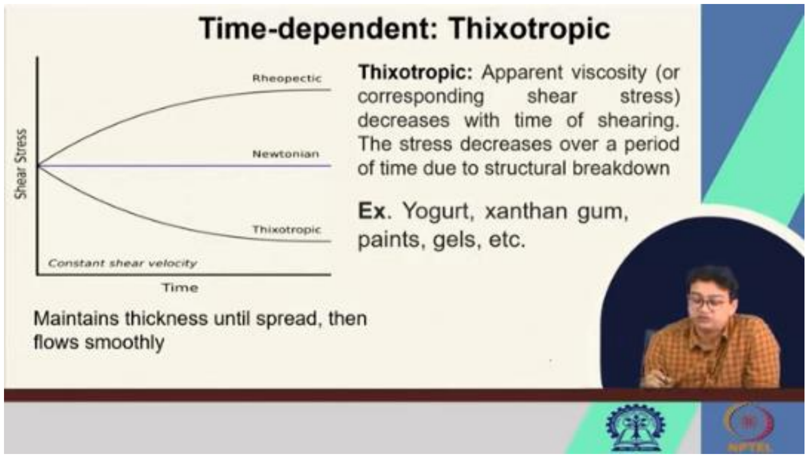


So, that is why it is called the apparent viscosity. So, apparent viscosity therefore, equals to K into du / dy to the power n minus 1. So, they will be very useful this knowledge will be very useful when we will be calculating the velocity profile and the pressure drop when the non-Newtonian fluid flows through a particular geometry . Now, coming to the next . So, these are actually very basic idea I want to give you the non-Newtonian fluid classification they are actually



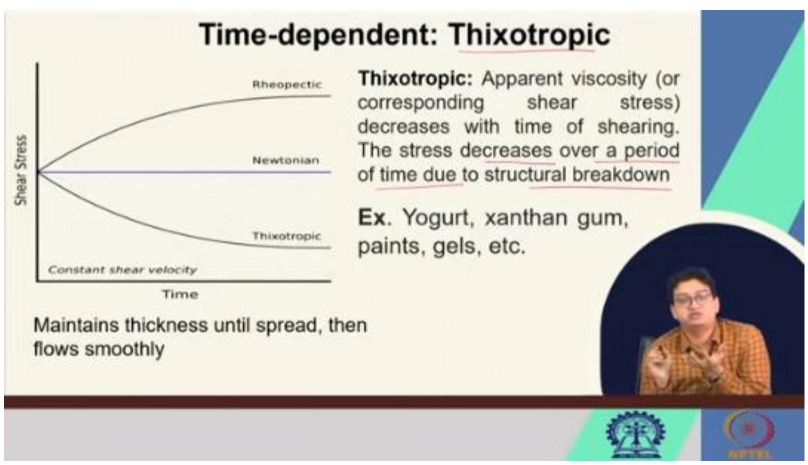
mainly two in nature time dependent and time independent. Time dependent of course, the name indicates the you know viscosity is depending on the time. Now, time independent the this one does not depend on the time. So, on the time dependent we have a thixotropic and rhiopectic and in the time dependent we can have pseudoplastic or shear thinning another one is Bingham plastic or viscoplastic, sometimes it is also called viscoplastic, dilatant or shear thickening.

Now, we will look into the detail, ok. So, we will start with the thixotropic and rheopectid followed by the time independent one. Now, what are those? So, in thixotropic, if you what it says the apparent viscosity or you know the corresponding shear stress decreases with time of shearing ok.



So, we have a food product now that is actually subjected to a shear. So, the longer you shear the apparent viscosity it will change and eventually it will decrease ok. Therefore, the stress also decreases over a period of time due to the structural breakdown ok. So, what happens? So, initially

When it is at rest. So, it is giving you some property; viscosity is there. Now, the moment it is subject to the shear state, that means the force is applied. So, there will be some structural breakdown that finally yields to the decrease in the apparent viscosity.

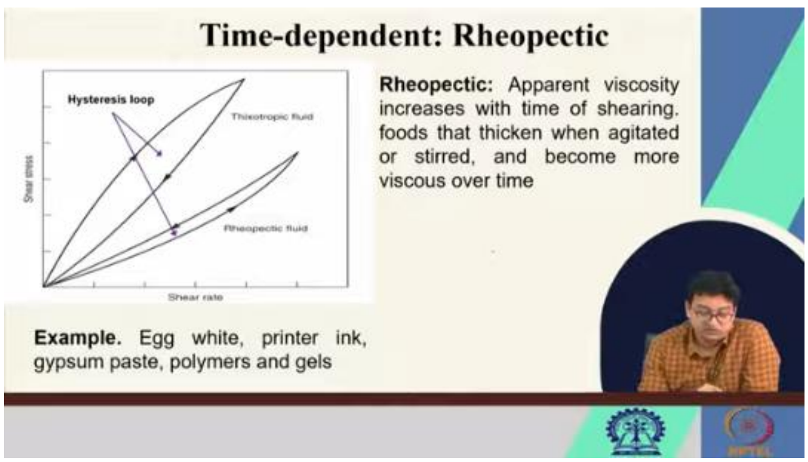


And if you look at the picture, here in the x-axis we have time, and here we have the shear stress, ok. The rheopectic one, sorry, the thixotropic one looks like this. So, it is starting from here, the shear stress over here, and eventually it is decreasing as the time progresses. This one is Newtonian. It is giving us a straight line parallel to the x-axis, ok.

So, it is not changing with time, but the thixotropic one is going down, ok. What are some food materials? Gums, yogurts, some paints, gels—they are actually thixotropic in nature. Now, you remember, If you take a food product, let us say honey, some varieties of honey can act as a Newtonian fluid, but honey of a different variety can also give us a non-Newtonian nature.

So, basically, this viscosity depends on the molecular structure, ok. So, we cannot wholeheartedly say that honey will always give the Newtonian profile, ok. It may not happen. It may also give a non-Newtonian profile, all right. Now, coming to the rheopectic part.

Now, what is rheopectic? It is also time-dependent. If you look at the picture over here. So, in the rheopectic, what is happening? So, we are slowly increasing the shear rate.

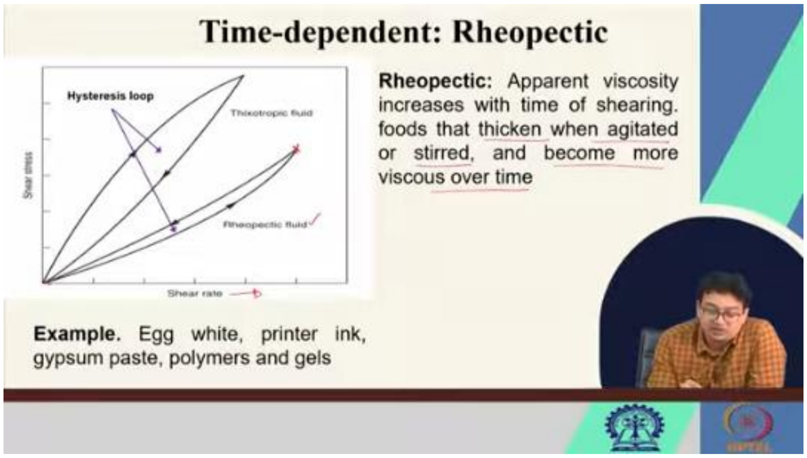


On the x-axis, we have the shear rate. So, we are slowly increasing the shear rate, let us say up to a maximum value over here. In the rheopectic, initially, the apparent viscosity was some over here. Eventually, with time of shearing, it is increasing. That means, say, if you have any food you are mixing.

So, in the food processing operation, if you want to take an example, you can have a lot of mixing and agitating. So, during this mixing process or agitating process, it may become much more viscous over the course of mixing or over the time period of agitating, okay? So, that means the food gets thickened when agitated or stirred and becomes more viscous over time. Now, what is happening over here? So, let us say initially we are applying some shear rate, and it is going up, and here we are stopping, okay.

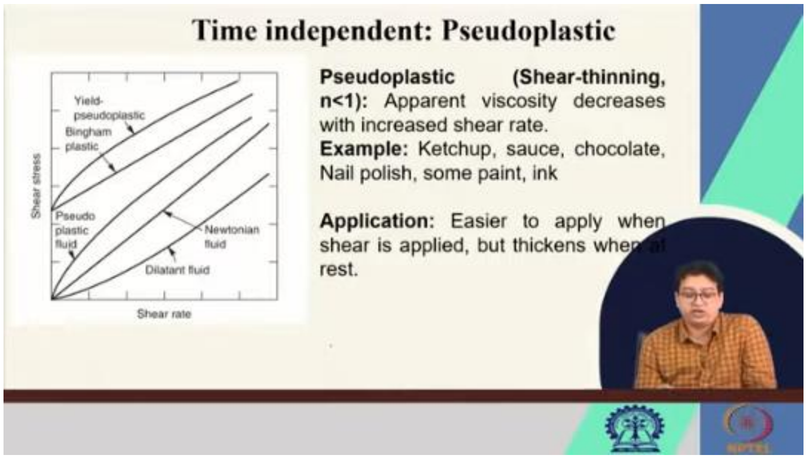
Now, we are going up to a maximum value. Again, from this maximum value with the same product, we are going down. That means shear stress and shear rate are going down.

So, you will see that it does not follow the exact same path; that is called the hysteresis loop. And why does this happen?

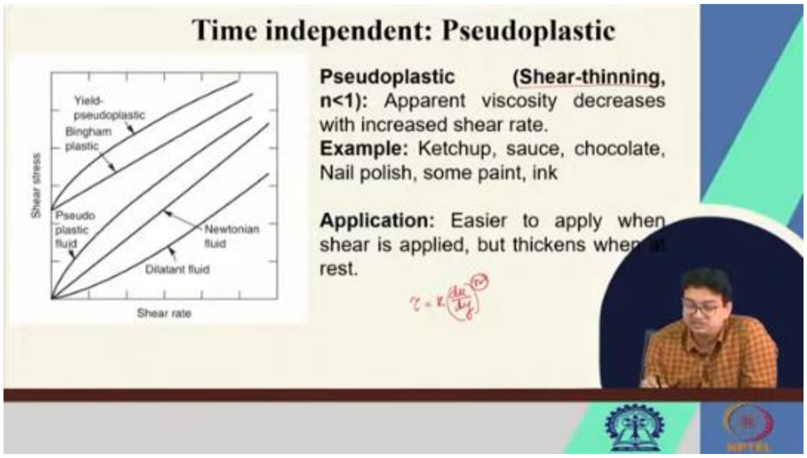


Because of the change in the molecular structure or structural changes again. What are some examples? Egg white, printer inks, gypsum paste, polymers, and some gels. So, if you have this kind of product, the more you agitate or mix, it may become more viscous. That means the apparent viscosity increases over the time period.

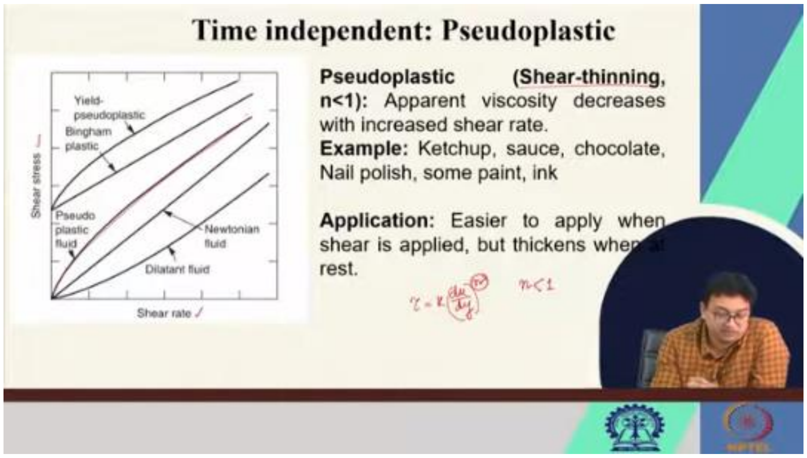
Now, coming to the pseudoplastic. So, pseudoplastic is time-independent, ok? So, that means this one is actually solely dependent on the time-dependent. The time-independent first one is the pseudoplastic. Pseudoplastic is also known as shear thinning.



So, if you recall, we had an equation of du dui to the power n. So, this is the flow behavior index. In pseudoplastic, shear thinning behavior has n less than 1, ok? That means apparent viscosity decreases with an increase in shear rate. So, here, if you look at this picture, this graph has the shear rate on the x-axis and shear stress over here.

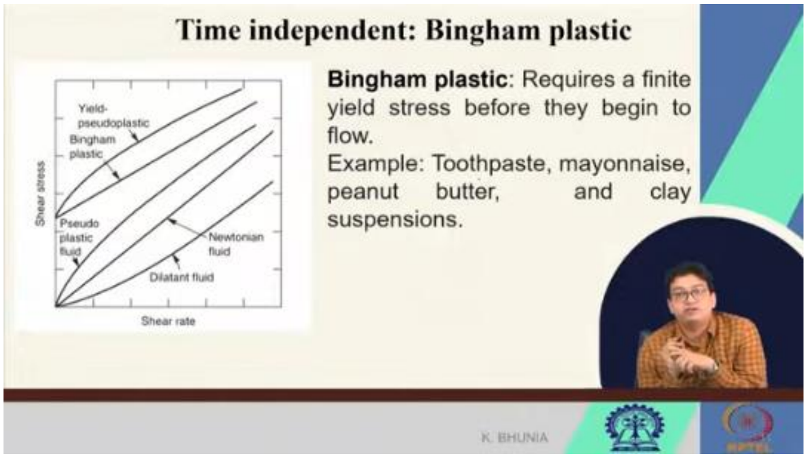


So, this one is giving the pseudoplastic nature, this one. Ok. So, apparent viscosity decreases eventually with increasing shear rate, ok? Over here, if you look at this one, this curve is also known as yield pseudoplastic. Why is it known as yield pseudoplastic?

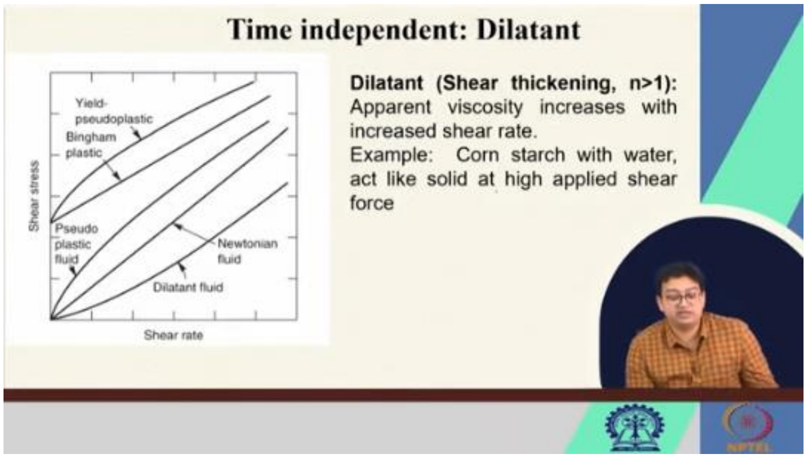


Because it has got some yield shear stress, that means it is behaving as a pseudoplastic. But to make it flow, we have to apply some initial force. That means the initial shear stress has to be applied. What are the examples? Ketchup, sauce, chocolate, nail polish, some different kinds of paints, inks.

So this is called the shear thinning or pseudoplastic. Now, coming to the Bingham plastic. Bingham plastics, as I if you look at over here, this one is the Bingham plastics. You look at the nature; we have some initial shear stress values here is the intercept, that is tau naught, OK. That means, in order to make it flow, we have to apply some initial stress.



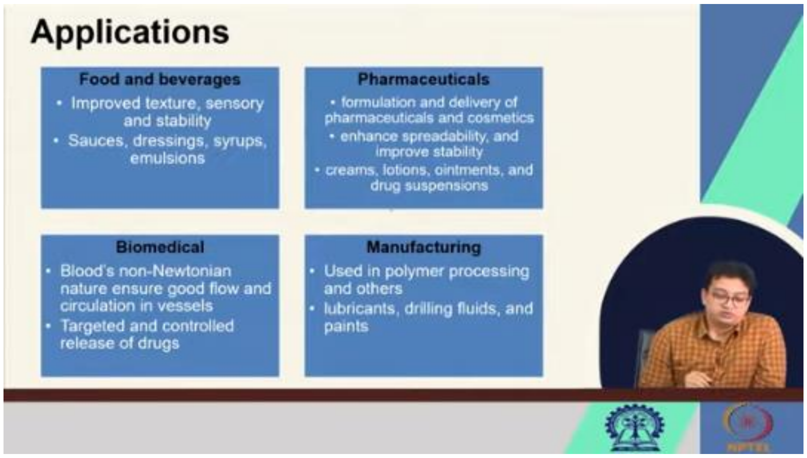
So, that is called the Bingham plastics, which require a finite yield stress before they begin to flow. So, toothpaste, this example I have already given. Some food products are mayonnaise, peanut butter, and clay suspension. Now, coming to the next part, the another time-independent one, that is called dilatant.



Dilatant, also known as shear thickening. So, as the name indicates, shear thickening means the more you apply shear, it becomes thickened. That means apparent viscosity will eventually increase with the increased shear rate. So, if you look at this graph, this one is actually dilatant, a time-independent dilatant. You look at the nature of this one: initially here, over here, it is going down a little bit, then eventually it is increasing. That means, with the application of the shear rate, the apparent viscosity is increasing, and the corresponding shear stress is also going up.

What are the examples? Corn starch with water, ok. So, corn starch with water—the more you mix it over the period, ok. So, it acts like a solid at high applied force, ok. So, if you apply a very high force of mixing, ok, or initial stress is applied.

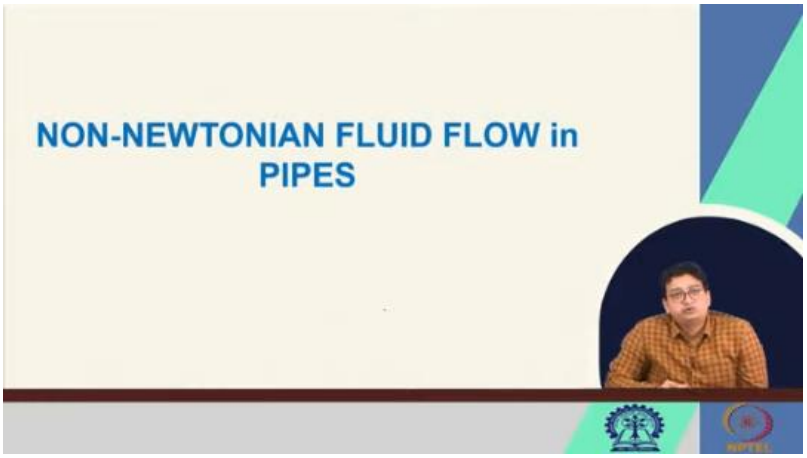
So, it will act like a solid, ok. So, now we have some basic fundamental ideas about what different kinds of non-Newtonian fluids exist in the food and beverage industries and how to classify them based on their behavior—that means, shear stress versus the rate of deformation. So, it has got certain applications also in the food and beverage industry, of course, which is our interest. So, what do these non-Newtonian fluids provide? They provide improved texture, different kinds of quality attributes, sensory mouthfeel, and can be found in sauces, dressings, syrups, and emulsions.



You know, in all our households, you may come across chocolate syrups, peanut butters, and of course, tomato ketchup, which are very common things. So, these are actually non-Newtonian in nature, okay? Additionally, they are also heavily and extensively used in pharmaceuticals, biomedicals, and manufacturing, okay? So, in pharmaceuticals, the formulation and delivery of different pharmaceuticals, drugs, and cosmetics are being used. What they actually do is, if you can tweak their properties, they can enhance spreadability and improve stability. And what are some examples? They are creams, lotions, ointments, and drug suspensions.

Now, in biomedicals, blood is non-Newtonian in nature, okay? So, because of its non-Newtonian nature, it ensures good circulation through our vessels and good flow as well. And in biomedicals, the targeted and controlled release of drugs also utilizes the properties of viscous fluids. Polymer processing and different kinds of additive manufacturing are being used. For example, lubricants, drilling fluids, and paints.

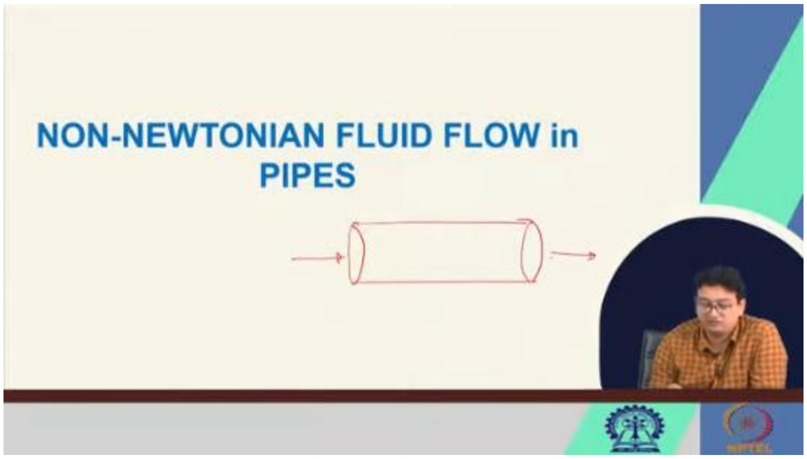
So, so far, what have we looked at? We have looked at the different kinds of non-Newtonian fluids, their classifications, some examples, and how they behave under stress conditions. Now, what will we do? We will slowly move to our main component, which is non-Newtonian fluid flow in pipes.



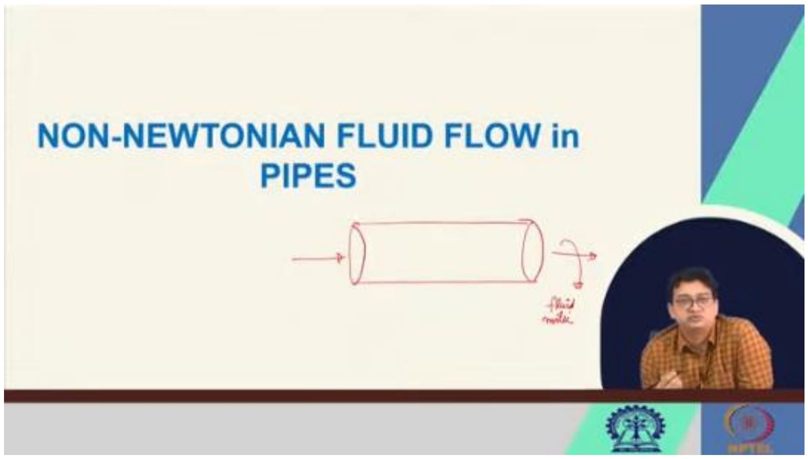
Now, here is the thing why it is very important. See, in the process industry, if you look at the food and beverage industry, the fluids are actually required to flow or required to be delivered from one place to another or from one zone to another. Even during processing, if you look at it, you can take a very simple example of the processing of milk, okay? Pasteurization of milk. So, how is it done? It is done, of course, in the dairy plant.

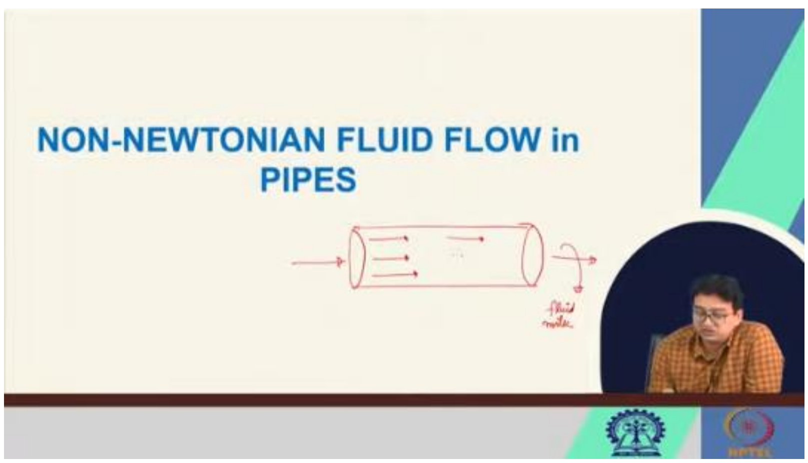
So, there are a lot of heat exchangers used where different kinds of pipes, you know, heat exchangers, are used to pump the milk at a certain flow rate, volumetric flow rate, okay, and what is the final aim? The final aim is to pasteurize the milk, okay. So, what is pasteurization? In pasteurization, we want to kill or inactivate the target microorganism, which is actually tuberculosis.

Now, the thing is, let us say you have a pipe, okay. So, if you have a pipe, okay, now the fluid is flowing, okay. The fluid is flowing through the pipe, okay. Now, In order to make it flow, we have to pump the fluid.



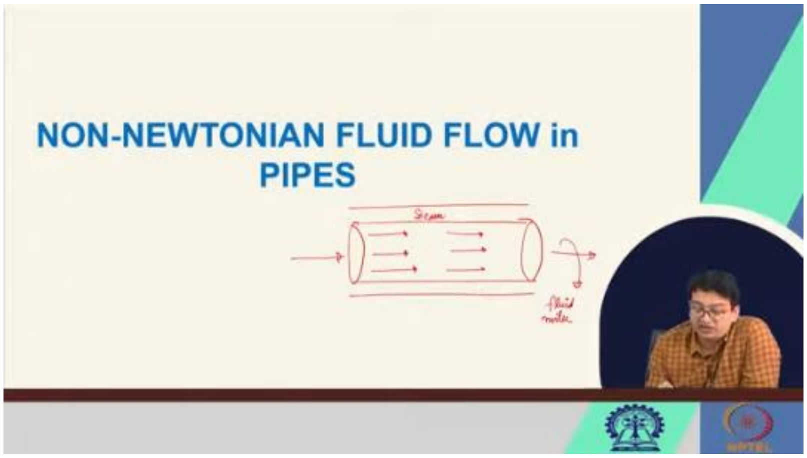
So, so that we can collect the fluid out of here, let us say here we have milk, ok, and we want a good temperature. So, what would be the temperature? Let us say you want to have a, you know, high-temperature short-time process. So, it will be, you know, at like 75 or 71 degrees C for a few seconds, ok. Now, when the fluid is passing through the pipes, ok. So, it has to be processed.



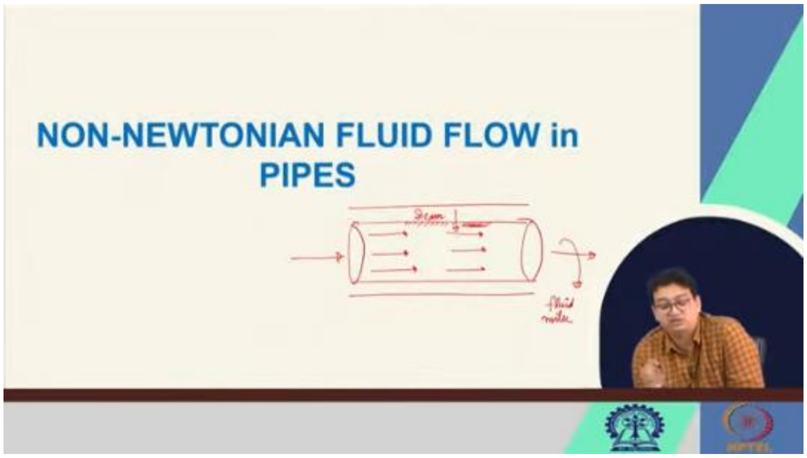


So, I am giving you a very generic example. So, although in reality, the things are much more complicated. So, let us say it is being processed with a jacketed vessel over here, ok. So, it is a concentric flow, and here you have maybe, ah, you know, a heating medium, some steam is there, ok. Now, it is passing through the tube, ok.

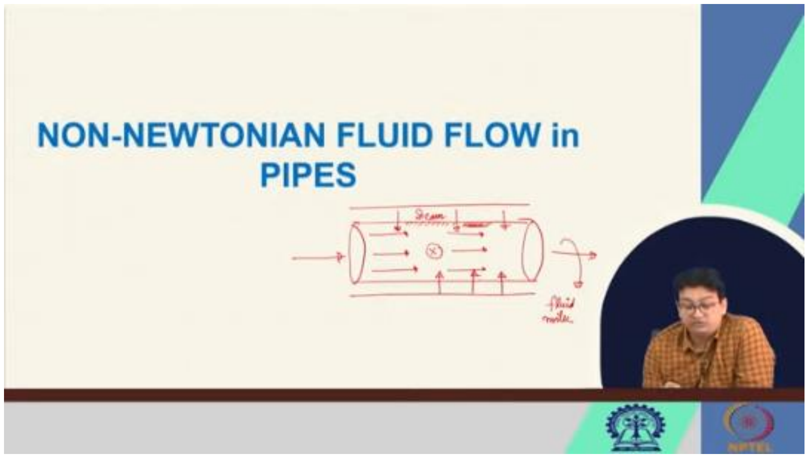
And eventually, what will happen? The temperature will transfer the energy will transfer from steam to liquid milk. So, the temperature will rise. Now, we do not know what the temperature distribution within this system would be. Now, why do we really want to look for the temperature distribution? Because we want to inactivate the target microorganism.



So, until unless the temperature is achieved, so we cannot make sure that it has been inactivated. Now, when this is flowing, we need to know the pattern of the flow. Why? Because the one the liquid that is over here that is just adjacent to the wall of the tube over here the internal tube that receives the heat the energy very fast. The temperature will go up very very fast.



Now the fastest or you know the slowest heating region is the mainly the central region. So, the flow energy flow will be like this. Now, this part is the least treated region, this thermal core. So, we have to make sure this part should achieve the desired temperature. So, in order to understand this profile, we have to have the good picture of or we have to visualize what is the velocity profile.



Now, since we want a certain volumetric flow rate because it is a let us say it is a commercial process we have to pump, we have to deliver ok. So, we have to know what would be the pumping power requirement and pumping power requirement is related to the frictional loss while the fluid is travelling through the pipe ok. So, let us say this is the length of the pipe ok. across or over this length how much pressure drop occurs that we have to understand ok. So, that is why we have to have the knowledge of the that the velocity profile and how to calculate the pressure drop of the equation.

Now, in the non-Newtonian fluid flow, apart from the Newtonian fluid flow, the non-Newtonian equations are a little bit different. So, that is what we will be looking at, all right. When we derive the flow of non-Newtonian fluids through pipes, we must have some knowledge of the continuity equation and the momentum equation. I hope you have learned this in the previous classes. So, I will quickly go through them at the very beginning.

I will explain a little bit, and you can also look at the previous classes, of course, to go through it and understand. Now, what do we have to do? Now, once we have the continuity equations and the momentum equation, we will apply some assumptions or considerations, along with the boundary conditions, to derive the pressure drop equation and velocity profile of non-Newtonian fluids in different geometries, all right. Now, friends, so far, what we have learned in our class is the basic definition of viscosity and how to classify different kinds of food based on their viscosity and behavior.

There are two types: Newtonian fluids and non-Newtonian, okay. For Newtonian fluids, if you plot the shear stress versus the deformation rate, it will give you a linear relationship that passes through the origin. Non-Newtonian fluids deviate from Newton's laws of viscosity, and they can be time-dependent or time-independent. Under time-dependent and time-independent categories, we have rheopectic, thixotropic, and also shear-thinning (pseudoplastic) where n is less than 1. We also have the dilatant type and, finally, the shear-thickening type.

So, in the next class, we will be looking at how to derive the pressure drop equation and how the velocity profile looks when a non-Newtonian fluid flows through pipes. Thank you.