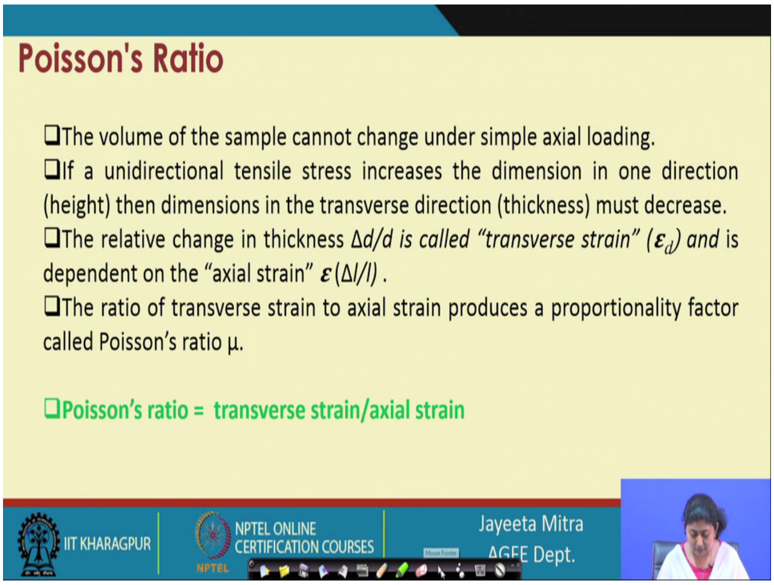
Fundamentals of Food Process Engineering
Prof. Jayeeta Mitra
Department of Agricultural and Food Engineering
Indian Institute of Technology, Kharagpur

Lecture – 03
Food Rheology (Contd.)

Hello everyone welcome to the NPTEL online certification course on Fundamentals of Food Process Engineering. So, we will continue with Food Rheology today; in the last class we have seen the material property of solid and we have also learned the three different modulus, that is Young's modulus, bulk modulus and shear modulus. And also we have familiar with certain parameter of the rheological nature of the solids and stress tensor also we have discussed a bit. And today we will move further to very important concept that is called the Poisson's ratio.

Now, when we have discussed about the unidirectional or uniaxial force; that time we have noticed that when we are pulling the body from the both end in a unidirectional manner the; so the elongation has happened in the body. That means, in the direction of the force, the body has been elongated some deformation or some lengths in hands in that direction right. Now since the body volume cannot be changed because we are not exposing it to the bulk compression right. So, in this case if suppose some changes happened in the longitudinal direction. So, definitely some amount of change will also need to happen in the transverse direction because the volume should remain constant right.

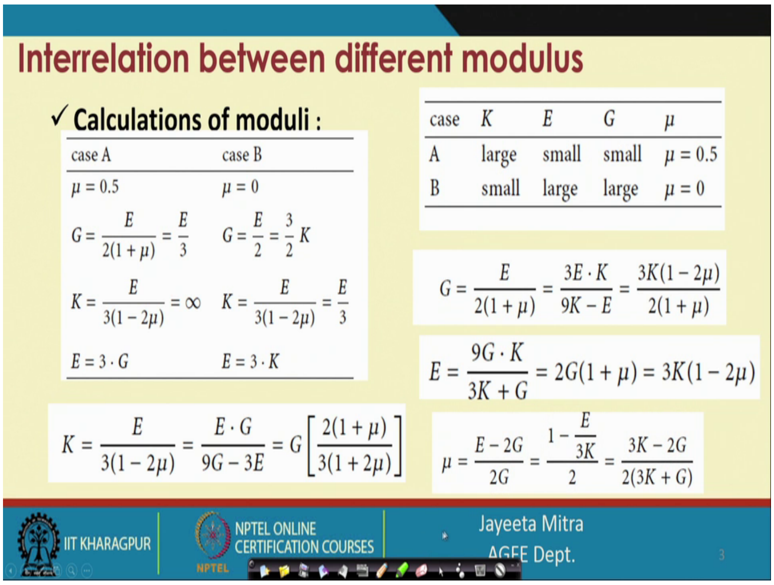
(Refer Slide Time: 01:58)



So, Poisson's ratio deals with this concept that is because the volume of the sample cannot change under simple axial loading. If a unidirectional tensile stress increases the dimension in one direction, the dimension in the transverse direction must decrease ok. And the relative change in the thickness that is delta d by d is called the transverse strain and the it depends on the axial strain that is delta l by l. So, the ratio of the transverse strain to the axial strain produces a proportionality factor that is called the Poisson's ratio mu.

So, Poisson's ratio mu that is equal to transverse strain by axial strain and this is very important parameter; if we know the Poisson's ratio and we know that any other parameter between all the 3 modulus that is E K and G; capital E capital K and capital G, we can find out the other parameters. So, the interrelation can be visible from this table that we have taken 2 material case A and case B.

(Refer Slide Time: 03:12)



So, in case A what we are getting that mu is equal to 0.5 and case B mu equal to 0; that means, mu is the Poisson's ratio. So, Poisson's ratio is transverse direction relative change in the transverse direction or transverse strain divided by the longitudinal strain ok. So, delta d by d divided by delta l by l; so, these values is equal to 0.5 that means the transverse strain that is equal to half of the longitudinal strain in the first case, where as in the second case the longitudinal strain is so high that mu value is coming 0 ok.

So, in the in this case if mu if mu is 0; 0.5 and mu is 0 in case of A and B we know that there are different interrelation like shear modulus G bulk modulus K and Young's modulus E that can be expressed in terms of these other modulus. So, if we try to find out how G or shear modules E divided by 2 into 1 plus mu where mu is equal to 0.5. So, G we are getting E by 3 that is one third of the Young's modulus will be the value of shear modulus ok.

Similarly K that is the bulk modules; so that is coming infinity ok, so bulk modulus coming infinity; now what is the bulk modulus? That is the relative change of pressure needed to cause the relative change in the volume. That means, the pressure the requirement of the pressure will be so high to cause the change in the volume in this kind of a sample and here because we have got this one in G equal to E by 3.

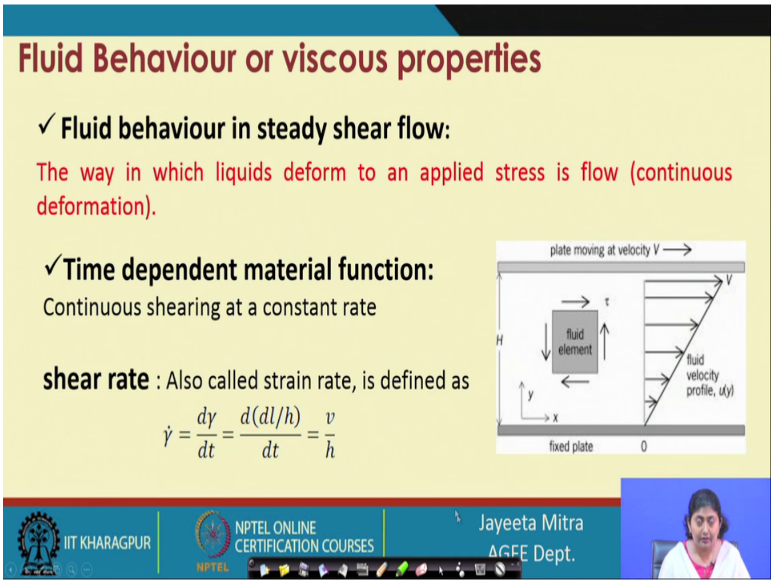
So, similarly E will be 3 times of the shear modules in case of B; however, we are getting G equal to E by 2 or 3 by 2 into bulk modulus here the bulk modulus is equal to E by 3.

So, in the first case we are getting shear modulus E by 3, in the second case we are getting the bulk modulus as E by 3. And further we can get the expression of K in terms of Poisson's ratio only that is Poisson's ratio in an shear modules; so all the interrelation can be generated. So, if we try to find all the; all the values of this kind of 2 material. So, from material A we are getting K is very large that we are getting from here.

So, the bulk modulus will be very large E is small Young's modulus is small; that means, if you if you plot this stress versus strain in this particular matter. So, we are getting a very low slope so; that means, the change of the change to cause a certain amount of strain small amount of stress is required ok. Similarly G is also we are getting small, but for material B where the bulk modulus is small. So, E we are getting very large and G also we are getting very large value ok. So, K G and E all we can relate with their; with the other property or in terms of the Poisson's ratio ok; so this is the expressions.

Now, we will move on to the next thing that is the fluid behaviour or viscous property. So, till now we have mostly concentrated on the on the solid behaviour rheological behaviour of the solid that what happen when a solid material is you know exposed to normal or shear stresses ok; also the concept of tensor stress tensor is very much applicable to the fluid. So, now we will going to see in a bit detail that what other the fluid behaviour or viscous properties.

(Refer Slide Time: 07:39)

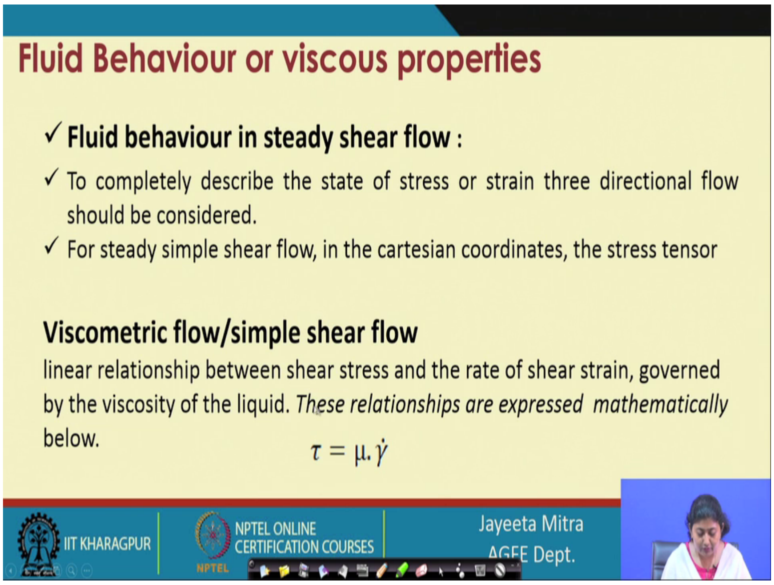


So fluid behaviour in a steady shear flow; so the way in which liquid form to an applied stress is flow that is the continuous deformation with time. So, let us take fluid which is kept in between 2 thin plates and the gaps between 2 plates are very less. So, each is very less and from the rest position if the bottom plate is fixed to the ground and we start giving the top plate of velocity. So, stop when the top plate starts moving with a velocity v in the x direction. So, it tries to pull all the fluid element or the molecules that is in contact with the plate, it also try to move it along the plate; however, the bottom plate is fixed. So, all the fluid element of fluid particle that is in contact with the bottom plate will try to restrict that flow ok.

So, they try to have in the same resting position; so because of that this kind of a profile will generate the linear profile will generate ok. So, if we want to measure the shear; in this case the shear rate that we can measure by how long the top plate has moved on the particular point and what is the distance between these 2 plate. So, if we consider the continuous shearing at a constant rate; that means, this top plate is moving with the fixed velocity v towards x direction, then shear rate that is also called the strain rate is defined as gamma dot ok. So, gamma dot is the shear rate or strain rate or rate of strain any way you can express it; that means, the change of shear with respect to time. So, d gamma by dt; so it is a time dependent material function, so now d gamma is the shear.

So, we can express this as small distance if it has changed. So, dl by h now dl by dt that that is a it is you know significance of the velocity. So, velocity divided by h; so if you want to measure here the strain rate, we can express it in terms of the v and h and here the delta l and h is very small that we have considered right.

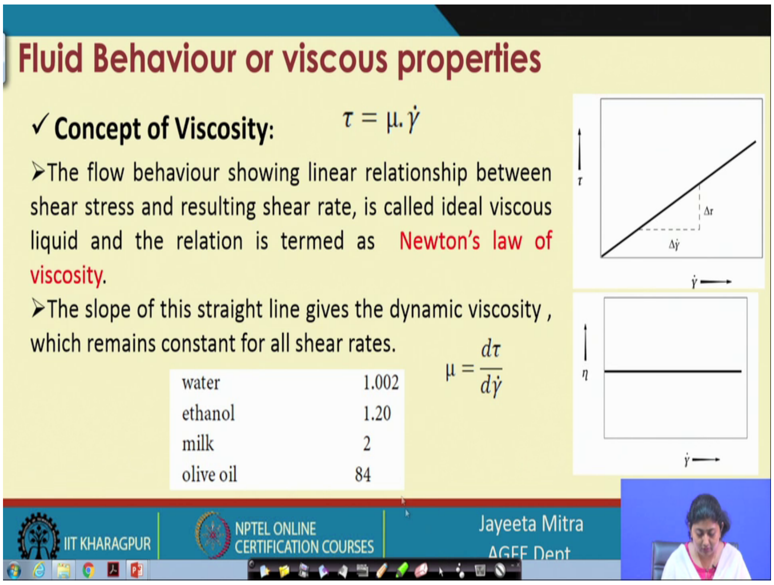
(Refer Slide Time: 10:37)



So, now fluid behaviour in steady shear flow; so, to completely describe the state of stress or strain three directional flow should be considered for steady simple shear flow. In the Cartesian coordinates, the stress tensor is used to express the flow as I have mentioned already in the last class.

Now, viscometric flow or simple shear flow; so, what is that; that linear relationship between the shear stress and the rate of shear strain governed by the viscosity of the liquid. Now what is viscosity? As we have seen in the in the earlier diagram that, if unidirectional shear stress is applied that is towards the x direction, the plate has been moved with a velocity constant velocity v; then because of the fluid property it try to resist the flow ok. So, that is termed as viscosity and if we plot the linear relation between the shear stress and shear rate we will get a straight line and the proportionality constant is mu or viscosity ok.

(Refer Slide Time: 12:06)

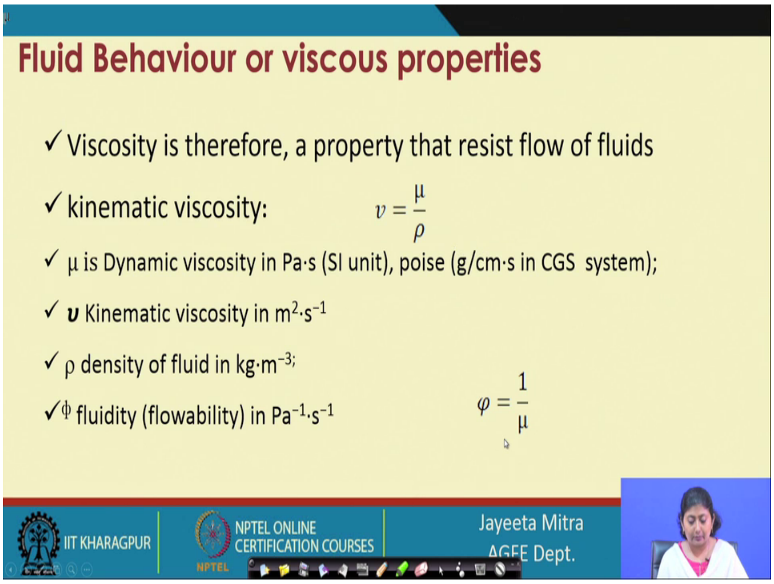


So, here is the expression graphical expression that is shear rate we have expressed in x direction and the corresponding shear stress which is expressed by tau that is being given in the y direction. So, straight line we are getting and from the slope we can get the idea of viscosity ok. Now, those materials which show this linear behaviour between the shear rate and shear stress is called the Newtonian material because they obey the Newton's law of viscosity. So, this tau is equal to mu into gamma dot that is the Newton's law of the viscosity and the fluid those will obey this law is called the Newtonian fluid.

So, in case Newtonian fluid; if we want to plot their viscosity at different shear rate; so we will get a straight line. Because from this plot also we can see that the slope does not change; it is a straight line. So, the slope is actually the idea of viscosity the concept of viscosity. So, any point; any increasing shear rate if you want to measure you will get the same slope. So, apparent viscosity does not change viscosity or apparent viscosity does not change. Normally in case of Newtonian fluid; the viscosity is represented by mu and in case of non Newtonian, we regionally express them by apparent viscosity eta and also this the slope that we are getting this system as dynamic viscosity.

So, dynamic viscosity here remains constant for all shear rate. So, dynamic viscosity mu that is equal to at any instant; if you want to measure that is d tau by d gamma dot. Now here are certain common liquid that is you know food only or the application of different food is related with this kind of liquids. So, in them we can see that for water this value of dynamic viscosity is 1.002; the unit is in Pascal second ethanol, we are getting 1.20 milk; we are getting 2 olive oil, we are getting 84. So, you can see that that viscosity is changing or increasing in this particular material.

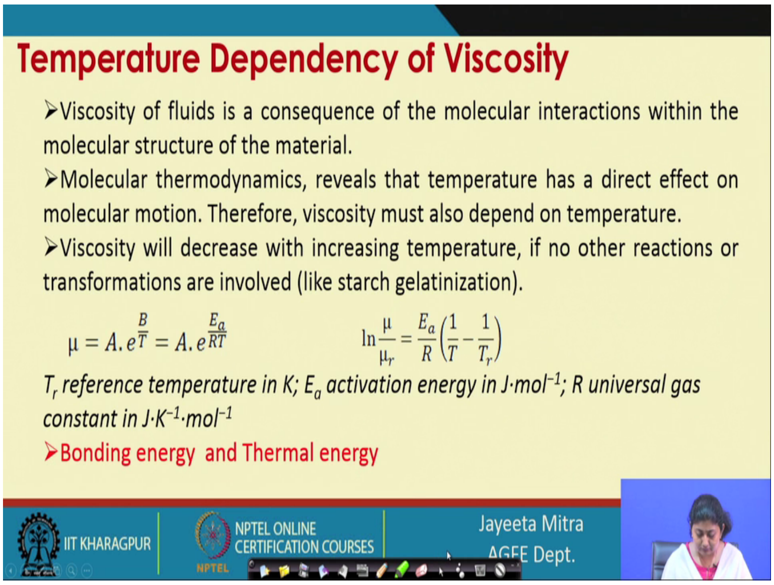
(Refer Slide Time: 15:08)



So, viscosity is there for a property, but resist the flow of the fluids and like we have learnt about the dynamic viscosity; we can also express the kinematic viscosity in terms of mu by rho ok. So, dynamic viscosity as I said that Pascal second is the unit in the in the SI scale poise in the CGS system and nu that is the kinematic viscosity expressed in meter square per second. This is actually the similar to the heat transferred alpha that is called the thermal diffusivity and also the mass diffusivity.

So, this is similar in case of the momentum transfer if you consider you will express the this particular parameter by the kinematic viscosity; rho is the density of the fluid in kg per meter cube and phi which is the reverse of viscosity this is called the fluidity or flowability ok; so flowability is just like 1 by mu.

(Refer Slide Time: 16:17)



Now, viscosity of the fluid is a consequence of the molecular interaction within the molecular structure of the material. So, this is very important because what happened that why we feel the you know viscosity or viscosity will change from material to material. Because there is molecular interaction playing a role and not the molecular interaction among all the material is not of similar type; there are different kind of interactive forces acting in them. And molecular thermodynamics reveals that the temperature has a direct effect on the molecular motion. So, there is a you know some kind of tradeoff happened between the thermal energy and the molecular energy intra molecular energy.

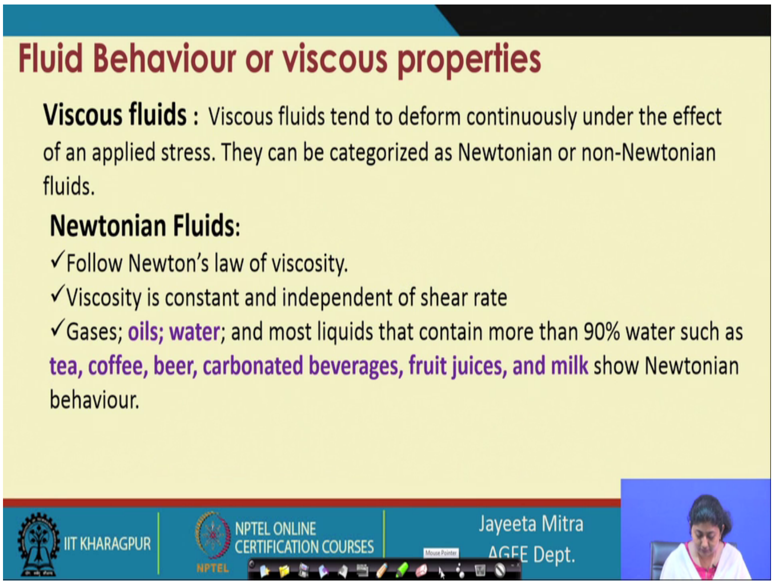
So, viscosity therefore, must also depend on temperature because some time when we apply heat to the material, what happened to the viscosity; for the for the liquid if you have observe that the viscosity lowers right and in case of the gas viscosity increases. So, the inter particular particle attraction or interaction force reduce because of the thermal energy and then the viscosity lowers; so the interaction plays an important role.

So, viscosity will decrease with increasing temperature; if no other reaction or transformation are involved some time say for example, starch gelatinization if we provide heat to the starch in the moist condition. So, gelatinize happen and that will change the structure of the material and gel formation will be there and the viscosity increases. So, the nature of the temperature dependency of viscosity can be expressed as arrhenius kind of equation.

So, mu that is equal to a constant A into e to the power B by T or it can be also written as A into e to the power E a by R T. So, B is equal to E a by R and E a is the activation energy, R is the universal gas constant; that means, if it follows this kind of an equation and one temperature at a particular temperature; if we know the viscosity then we can express the viscosity at any other temperature following this behaviour right.

So, this is a representation that ln of mu by mu r that is equal to E a by R into 1 by T by T minus 1 by T r. Because for a particular fluid if you are considering; so activation energy will be same, R will also be same, but T is different temperature will be different and because of that the viscosity will be different. So, for any fluid we can apply this equation to see the temperature dependency of viscosity ok. So, this is the normal expression the units of all these parameters. So, as I said that bonding energy and thermal energy; these 2 will play a role in you know increasing or decreasing the viscosity ok.

(Refer Slide Time: 20:08)

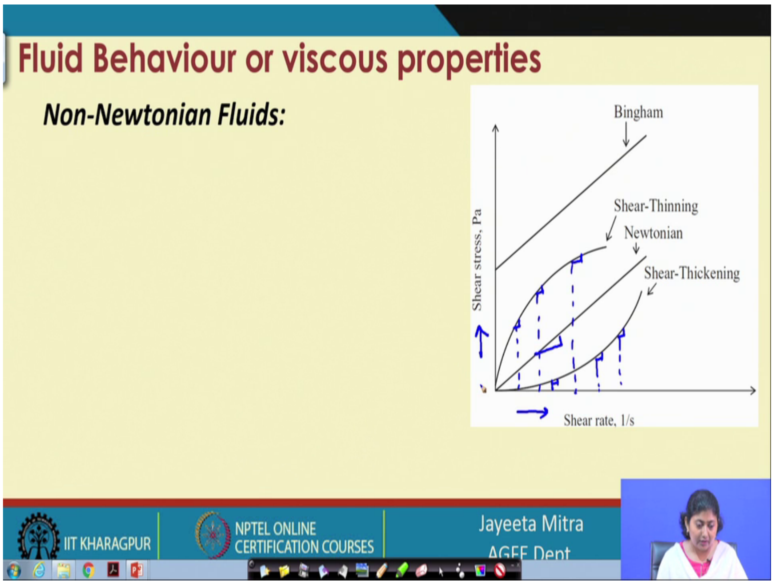


So, next is viscous fluids; so viscous fluid tend to deform continuously under the effect of an applied stress they can be categorized as Newtonian or non-Newtonian fluid. So, by now what we have learned is that if we apply a steady shear on a material that will flow instantly those are fluid material.

But if we plot the nature of the shear stress and shear rate in y and x directions respectively. So, what is the nature of that plot? Ok if that nature is linear then those fluids will be considered as the Newtonian fluid. And if they are not linear then we can termed as the non-Newtonian fluid ok. So; obviously, Newton's law of fluid Newtonian fluids; they we will follow the Newton's law of the viscosity and viscosity is constant and independent of shear rate.

For example, gases, oils, water and most liquid that contain more than 90 percent water such as tea, coffee, beer, carbonated beverage, fruit juices and milk ok; so, these show Newtonian behaviour right. So, definitely you need to take a fluid element if you if you consider whole vegetable or fruit. Although sometime they consider you know they have higher than 90 percent water, but they cannot be considered here you have to look for the fluids ok.

(Refer Slide Time: 22:01)

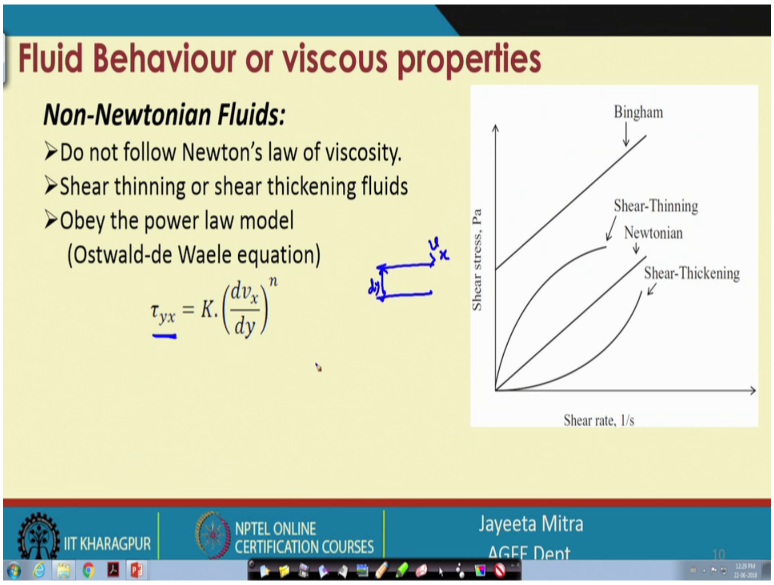


So now non-Newtonian fluid; so, here is the plot that shear rate and shear stress we have plotted in x and y direction respectively. So, the straight line the straight line where the slope constant that comes under Newtonian you know that already. Now these 2 plot where we are getting one curve that is changing its slope at every instant of changing in the shear rate and as shear rate increases ok.

As shear rate increases, we are getting a decrease slop right; similarly the other the lower curve if you can see where which change in shear rate; we are getting an increase slope right. The other particular nature here we can observe that is the straight line, but that straight line does not pass to origin ok.

So, all such characteristics that is deviating from the ideal Newtonian behaviour, where the stress and strain shear rate relation will be straight line and that will pass to the origin is not being fulfill. So, these all are comes under the non-Newtonian fluid ok.

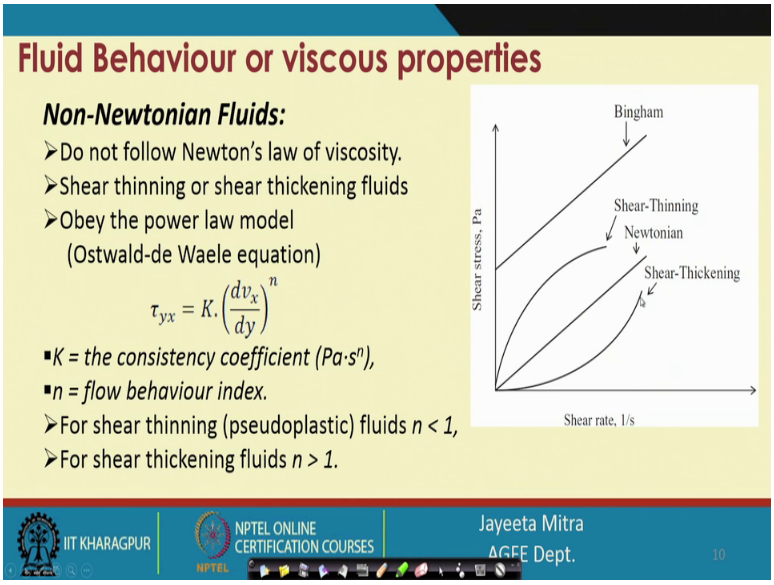
(Refer Slide Time: 23:38)



So,; so they do not follow the Newton's law of viscosity shear thinning and shear thickening fluid and they obey the power law model this is also called the Ostwald-de Waele equation; that is tau yx is equal to K into dvx by dy to the power n.

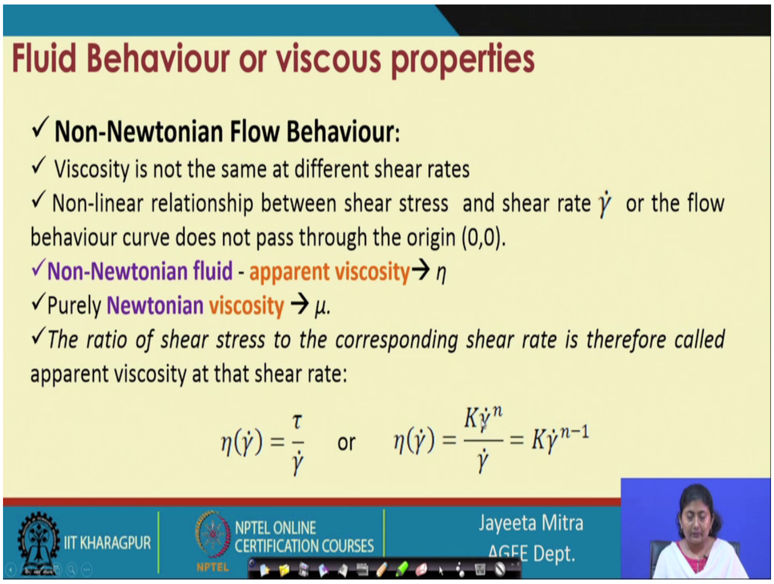
So, see tau yx; that means, if we consider the floor is in is in x direction you are considering the flow is in x direction; so vx. So, the stress shear stress felt in y direction because of flow in the x direction. So, that it that it indicates a dimension in my last class as well. So, this is the shear stress tau yx that is equal to K into dvx that is change in the velocity dvx in the dy ok. So, this is it now we can see here we have power n as well as it is called the power low model.

(Refer Slide Time: 24:44)



So, K is the consistency index and n is termed as the flow behaviour index. So, the unit of K is in Pascal into second to the power n and n is the flow behaviour index for shear thinning fluids. As I said that the slope is decreasing; that means, viscosity is decreasing with every increase in the shear rate. So, then n is less than 1 and the other case where the shear thickening happened n is greater than 1.

(Refer Slide Time: 25:16)



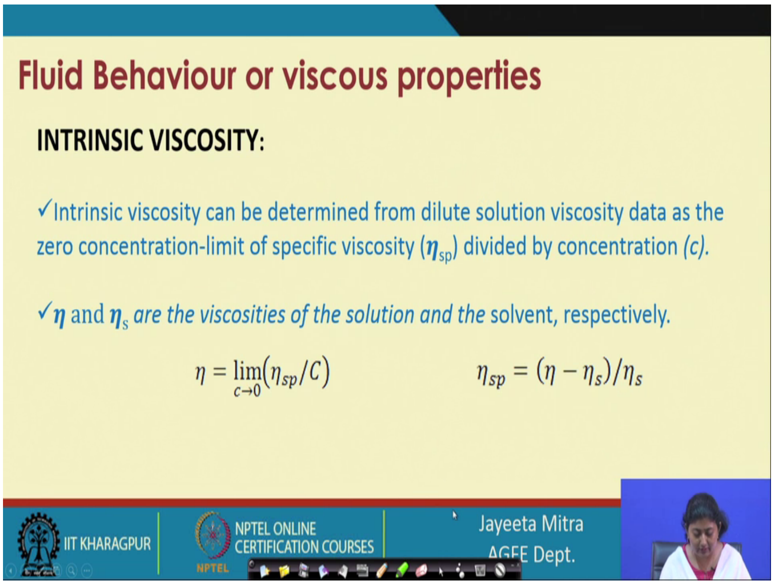
So, non-Newtonian flow behaviour that is viscosity is not the same at different shear rate non-linear relationship between shear stress and shear rate gamma or the flow behaviour curve does not pass through the origin. That is another case happen in case of bingham plastic fluid ok.

So non-Newtonian fluid that is why we call the apparent viscosity eta and for the purely Newtonian viscosity; Newtonian fluid we use the viscosity mu now the ratio of shear stress to the corresponding shear rate is therefore, called apparent viscosity the ratio of shear stress ok. Shear stress to the corresponding shear rate is therefore, called the apparent viscosity at that shear rate because as shear rate changing this value also change.

So, eta which is the apparent viscosity that is a function of shear rate here because at a fixed shear apparent viscosity, it will it will vary at different different shear rate. So, eta at a fixed shear rate gamma dot because it is a function of gamma dot that is equal to tau by gamma dot. Because ultimately what is apparent viscosity; if we if we plot the shear stress versus shear rate ok, then we get the slope of that that is called the apparent viscosity.

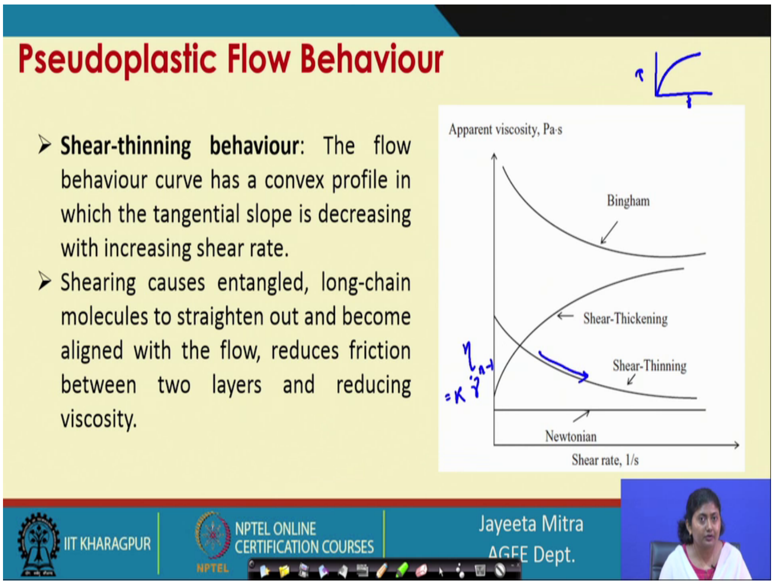
So, this apparent viscosity is which is, viscosity in case Newtonian that is fixed that does not change with the shear rate. But here it is changing with the shear rate in case of non-Newtonian fluid; so, what we can write is we can write eta of gamma dot tau is here K that is the consistency index into gamma to the power n because it follow the power law equation by gamma dot. So, we can write K into gamma dot to the power n minus 1; so this whole term is referred as apparent viscosity consistency index into shear rate to the power n minus 1.

(Refer Slide Time: 27:37)



So, intrinsic viscosity; what is it intrinsic viscosity can be determined from dilute solution viscosity data as the 0 concentration limit of specific viscosity eta sp divided by the concentration C. So, eta and eta s are viscosity of the solution and the solvent respectively. So, eta is limit concentration tends to 0 eta sp by C and eta sp equal to eta that is the viscosity of the solution minus eta s that is viscosity of the solvent divided by eta s.

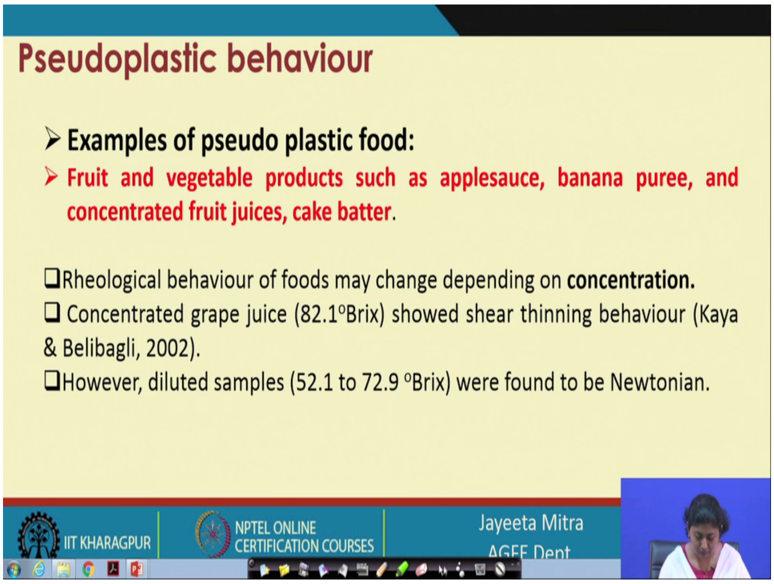
(Refer Slide Time: 28:18)



So, as I mentioned that shear thinning behaviour, where we can we can observe that the apparent viscosity is decreasing with increasing shear rate. So, this is shown by this strain; so apparent viscosity here we are plotting eta that is equal to K into gamma dot to the power n minus 1.

So, shear thinning is this behaviour and the flow behaviour curve has a convex profile in which the tangential slope is decreasing that we have seen in our stress versus strain shear rate plot ok. If you remember the tau with respect to gamma got we have got this kind of a plot for shear thinning and the reverse we have got for the shear thickening. So, shearing causes what kind of changes in a food ok. So, it causes entangled long chain molecules to straighten and because of their straighten out they become aligned with the flow reduces friction between the 2 layers and also reducing the viscosity. So, because of this kind of nature some food or some material show this kind of behaviour where upon higher shear or increasing shear rate their viscosity reduces.

(Refer Slide Time: 30:01)

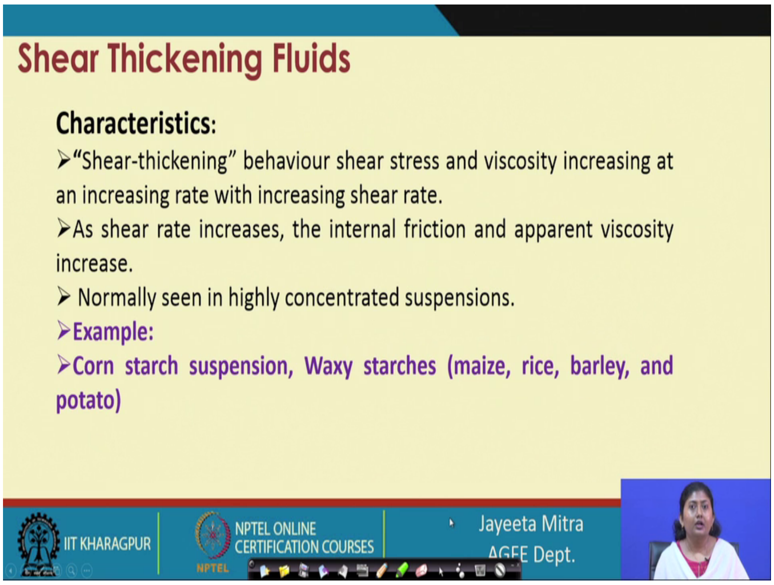


So, example of this pseudo plastic food; that is shear thinning food are fruit and vegetable products such as applesauce banana puree and concentrated fruit juice cake batter etcetera. So, for all this is if you put higher shear rate; we can we can get the viscosity as will be reduced. Now, rheological behaviour of the food may change depending on concentration ok; so, because they are they are not that is why the concept of the intrinsic viscosity is important. Because when the concentration is high then the viscosity will change and sometime it also happened that because of higher concentration sometime agglomeration may also happen. So, the bonding in shears between the; the fluid and the particle will be changed and the particle interaction will increase right.

So this happen in case of concentrated grape juice where 82.1 degree Brix showed shear thinning behaviour; however, diluted sample that is 52.1 to 72.9 degree Brix were found to be Newtonian. So, what happened is that you know when see 52.1 to 72.9; so this much degree Brix concentration when we have considered. So, we are getting a Newtonian trend ok; that means, as shear stress is increasing shear rate is also increasing shear stress is increasing right. Now what happened that when we reach is a higher concentration then may be the you know the grape juice in that the particle that that were emerged. So, they will be coagulated or they will be agglomerated ok.

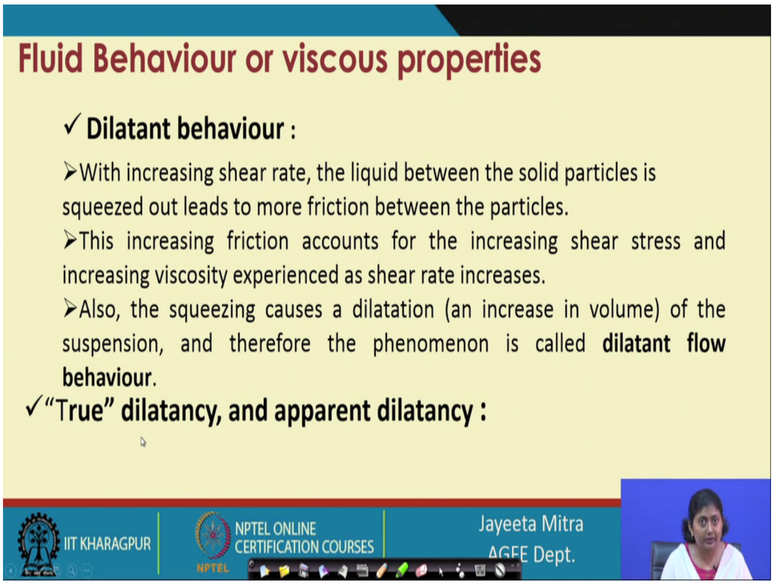
So, because of that what happen that their interaction with the fluid particle will be lowered ok. So, shear thinning behaviour we can observe; so because of that agglomeration the behaviour of the liquid will be totally changing.

(Refer Slide Time: 32:10)



The reverse strain that is shear thickening which is the behaviour where shear stress and viscosity increasing at an increasing rate with increasing shear rate. So, normally this is seen in high concentrated suspension; for example, corn starch suspension waxy starch that is maize, rice, barley and potato.

(Refer Slide Time: 32:35)

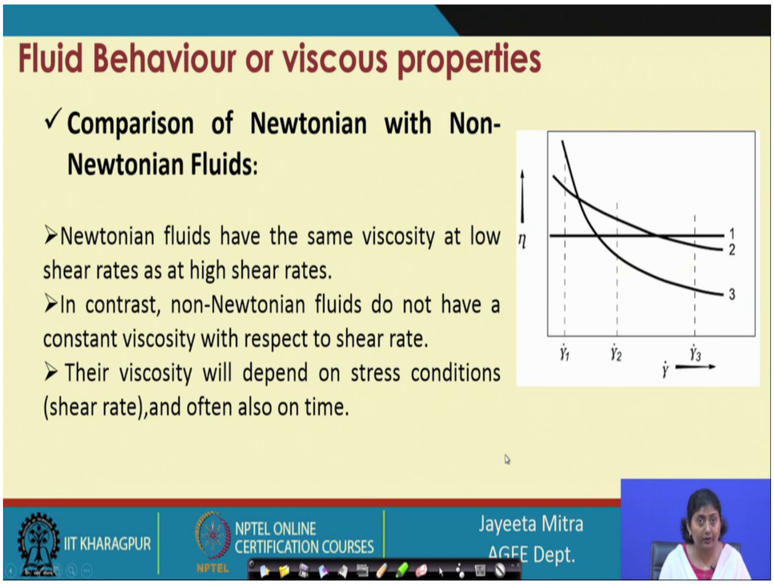


And this also called the dilatant behaviour that is with increasing shear rate the liquid between the solid particle is squeeze out and in turn more friction will be generated right. So, this increasing friction account for increasing shear stress and increasing the viscosity experience as shear rate that is also increasing, but because of squeezing it causes dilation that increase in volume of the suspension and therefore, this phenomenon is called the dilatant flow behaviour.

Now, you often may get to get to accommodate with this term like true dilatancy and apparent dilatancy ok. So, true dilatancy means that when you apply the increasing shear rate your behaviour changes; that means, your shear thickening happens. But when you withdraw the stresses or the shear rate is again come to 0 you can get back the initial viscosity.

So, those materials show the true dilatancy, but certain material because of their structural permanent changes permanent structural changes may happen in them. So, when the shear rate is again reduced to 0, also their viscosity does not come to initial condition right; so, those are called the apparent dilatancy.

(Refer Slide Time: 34:05)



So, simply if you compare the apparent viscosity with increasing shear rate for Newtonian for lower and higher shear; you will get the same apparent viscosity where as the non-Newtonian fluid; you cannot be sure of; they may go very low with higher shear rate or even go little bit lower compared to the Newtonian or compared to their initial value when the shear rate is increasing ok.

So, this is the different kind of nature we can observe. So, therefore, the viscosity will depend on the stress condition that is shear rate and often on also time in case of the non-Newtonian fluid. So, we will stop here I will continue the next class.

Thank you.