Transport Phenomena of Non-Newtonian Fluids

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Lecture - 01
Newtonian Fluids and Classification of Non-Newtonian Fluids

Welcome to the MOOCs course Transport Phenomena of Non-Newtonian Fluids. As the title indicates this course is entirely on the transport phenomena of non-Newtonian fluids specifically. So, what we will be discussing starting with? We will be starting with a few basics of non-Newtonian fluids then how to measure or estimate the rheology of this non-Newtonian fluids.

Then a few basics of transport phenomena that we might have already studied in previous UG level course. And then we will be applying this transport phenomena principles especially for the non-Newtonian fluids. That is how we will be progressing about this course.

This is our first lecture. So, then what we do? We start with a few basics of non-Newtonian fluids and then classifications. So, however, before going into the details of non-Newtonian fluids; if you have a kind of recapitulation of Newtonian fluid and then its characteristics, it will be easy for us to define a non-Newtonian fluids.

Because in simple terms what we can say? We can say that any fluid that does not obey the Newton’s law of viscosity then we can say it is a non-Newtonian fluid right. So, then if you have a kind of different characteristics of a Newtonian fluids different ways we can define the non-Newtonian fluids.

So, that is the reason we start with a few basics of a Newtonian fluids that we already know. The title of this lecture is Newtonian Fluids and Classification of Non-Newtonian Fluids.

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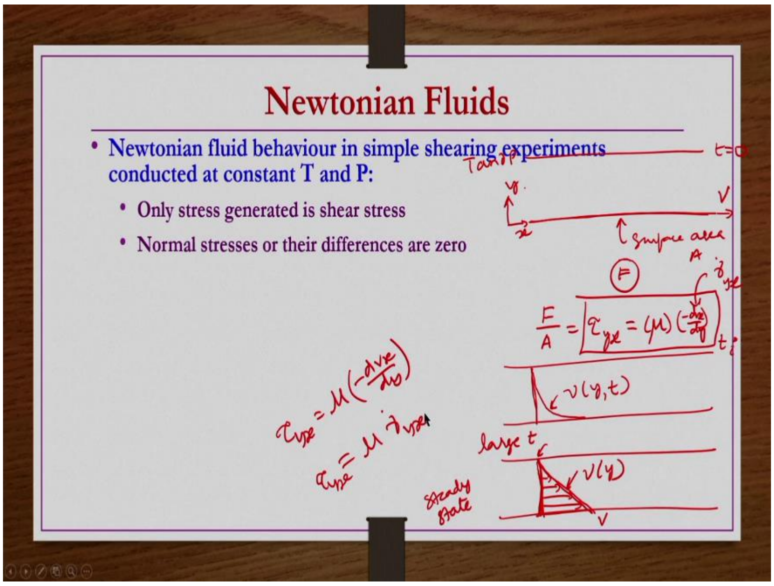

Let us say in order to have a kind of a brief recapitulation of a Newtonian fluid definitions. So, then what we do? We take a case where you know we have two planes like this, they are parallel to each other. And then we take a fluid between these plates, then we take we consider a fluid between these two plates at constant temperature and constant pressure right.

So, then what we do? We take, we apply certain kind of force to one of the plates right. So, let us say if you are applying certain force to the bottom plate right. So, the surface area of the bottom plate let us say if you take it has A. If you are applying the force F to this plate shearing force F.

So, what we have? Whatever the shear stress that is there that we can define $\frac{F}{A} = \tau$. So, we need to have a suffix for this subscripts for this τ. So, then what we have? We have to define the coordinate system. So, then let us say we are taking this direction as x direction this direction as y direction.

So, now this whatever this force is there that we are applying in x direction and then it is because of the force whatever the shearing motion that is there it causing some kind of stress and the plane which is perpendicular to this x direction.

So, that plane perpendicular to this one is y. So, that is the reason τ_{yx}we call it and then this is nothing but you know some something multiplied by elastic gradient that is what we know right.

Before directly going into the definition what we do? So, initially at time t = 0, we when you said this bottom plate to motion with velocity V. So, then you do not see any velocity profile this is at t = 0, but the same thing if you see gradually if you increase the time at certain time t = t; t_i or t_j whatever you call it.

So, what happens? So, then velocity profile if you see so, it will be something like this right and then this velocity profile you see it as a function of both y and t right. Gradually at large t if you do for longer period of time the shearing experiment.

So, at large t when steady state is developed then what you can see? This velocity profile is a linear because this distance between two plates we are taking very small distance. So, then what we have this velocity profile at steady state? It will develop a linear velocity profile like this.

So, then here the v is function of y only it is not function of time. So, the velocity profile is like developed like this. So, since the bottom plate is moving at velocity capital V it will be having the maximum velocity at the bottom most layer fluid layer will be having the largest velocity of V.

Since the top plate is stationary, we are not moving it. So, the top most layer of the fluid will be having 0 velocity. And then as y increases the velocity gradually decreasing some maximum velocity v to whatever the 0 velocity because y direction is going up. So, that is increasing why the velocity is decreasing. So, then shear stress whatever is there that is proportional to the shear rate that is $\left(\frac{-dv_x}{dy}\right)$. And then the shear stress is directly proportional to the shear rate and then there is a proportionality constant that is viscosity μ right.

So, this is what we know about the Newtonian fluid definition. So, any fluid that obeys this τ_{yx} directly proportional, linearly proportional to the shear rate then we call it as a kind of a Newtonian fluid.

Then we have whatever the proportionality constant is there that we call it as a viscosity right. So, this shear rate here in this case it is negative as y increasing the velocity is decreasing. So, then velocity gradient that you are going to have a negative one. So, then that is the reason here we have the $\left(\frac{-dv_x}{dy}\right)$. And then this indicates, this we represent by $\dot{\gamma}_{yx}$.

So, for Newtonian fluid what we have? $\tau_{yx} = \mu\left(\frac{-dv_x}{dy}\right) = \mu\dot{\gamma}_{yx}$ this is what we have. This is for a simple one dimensional motion. Now, here what we have taken actually we have taken a velocity variation in only one direction, the velocity is varying in the y direction and then velocity is there in only in the x direction; x directional velocity is varying in the y direction that much only information we have taken.

But in general, we may have other components of velocity and then they may also be changing with the position in all the direction that is possible. So, then we need to have a kind of generalized expression for this one. So, that also we know already we know it as.

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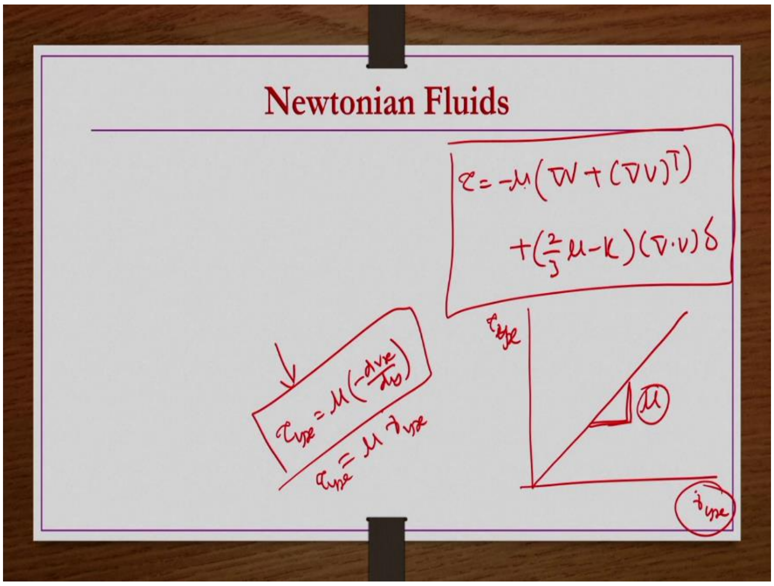

So, we know it as a let us say $\tau = -\mu(\nabla v + (\nabla v)^T) + \left(\frac{2}{3}\mu - \varkappa\right)(\nabla . v)\delta$. This is the generalized expression for the shear stress right. So, now, coming back to this one dimensional case $\tau_{yx} \propto \dot{\gamma}_{yx}$ and then proportionality constant is the viscosity μ.

Then if you plot it, if you plot it on x-y coordinates y you take y-axis you take τ_{yx} and then x-axis you take it $\dot{\gamma}_{yx}$. So, then what you get? You get a straight line passing through the origin straight line passing through the origin and then slope is μ right.

So, that is the viscosity. So, now, what does it mean by? Even if you increase the $\dot{\gamma}_{yx}$ whatever the value or even if you decrease the $\dot{\gamma}_{yx}$ it is not going to change, it is going to have the same constant viscosity μ slope is not going to change that is what we know.

And then even if you shear it for longer time or smaller time or whatever the time that you do, as long as the temperature and pressure is constant. So, this curve is not going to change this curve is not going to change and in such fluids are known as the Newtonian fluids such fluids are known as the Newtonian fluids right.

So, in terms of the other characteristics also if you see we have so many n number of characteristics for this Newtonian fluids those we are going to see now. So, now, if you get into the details of more characteristics of the Newtonian fluids what you understand?

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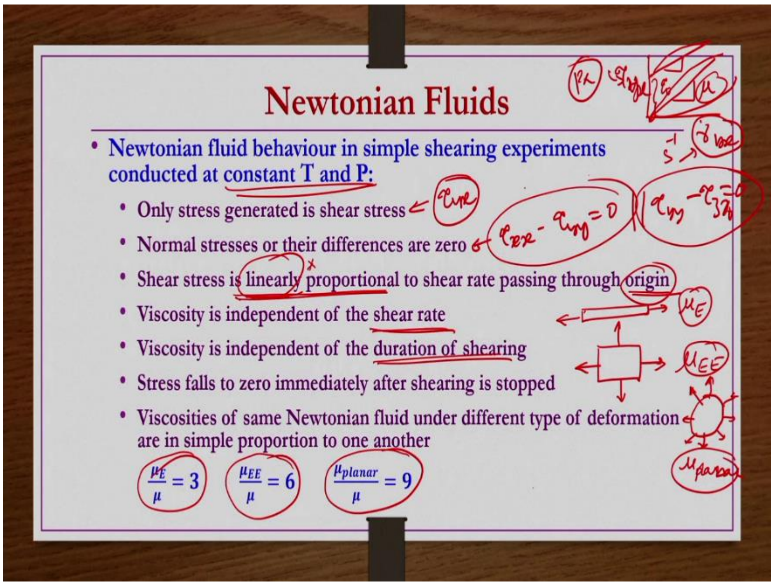

Newtonian fluid behaviour in simple shearing experiments conducted at constant temperature and pressure only stress that you find, only stress that you get in such kind of fluids is the only shear stress, only stress generated is shear stress. And then whatever the normal stresses; normal stresses are also possible because of the flow viscous flow.

So, then those normal stresses are 0, identically 0 or their difference is 0 for the Newtonian fluid right. So, whatever the shear stress let us say here in this case for simple shear stress for simple 1D experiment that we have seen τ_{yx} right. So, normal stresses or their differences are 0, because in general you know this τ_{xx} τ_{yy} are also possible. So, then identically they are 0 or their difference is also 0 τ_{yy} is 0 τ_{zz} is 0 or their difference is also 0.

So, that is what other characteristic of the Newtonian fluid right. So, then what we see? As I already shown this shear stress is linearly proportional to the shear rate and passing through the origin that we have seen just now when you take a Newtonian fluid and then get the τ_{yx}versus $\dot{\gamma}_{yx}$information you, then you if you plot it what you get? You get a straight line passing through the origin with the slope μ which is nothing but the viscosity right.

Then viscosity is independent of shear rate. Shear rate whether this $\dot{\gamma}_{yx}$it is small or large or medium whatever the shear rate, whatever the rate at which you are doing the shearing experiment this viscosity is not going to change as long as the temperature and pressure are remaining constant right.

$\dot{\gamma}_{yx}$ in general having the order of 10^{-3}or 10^{-2}or even lesser what we call? That is a low shear rate is in general is known as if $\dot{\gamma}_{yx}$ is having you know 10^4 or 10^5 or even higher then we call it you know this high shear rate. In between we call it as a kind of intermediate or more intermediate range of the shear rate ok.

The shear rate is having units of second inverse and then this is having nothing but the Pascal right. So, then viscosity should be having the units of Pascal seconds. So, that viscosity is independent of the shear rate whether it is if you are doing the shearing experiment at $10^{-2}s^{-1}$ or $10^{2}s^{-1}$or $10^{20}s^{-1}$whatever the shear rate that you do consider for the shearing right.

As long as the temperature and pressure you are maintaining constant then viscosity is not going to change for a Newtonian fluid ok. Then viscosity is independent of the duration of shearing whether this shearing experiment if you are doing for 1 hour or 1 day or 1 month or whatever it is as long as the temperature pressure you are maintaining constant and there is no fluid loss because of the viscous dissipation or thermal losses etcetera.

So, this viscosity is not going to change you know because of the duration of shearing. It does not change because of the duration of shearing. So, you do you take a Newtonian fluid if you do the shearing for the 20 minutes, if you do the shearing for 20 hours or if you do for you know even more time. So, it is not going to change as long as the temperature pressure are remaining constant.

Then stress falls to zero immediately after shearing is stopped. So, because stress whatever the shear stress is there now if you are stopping the shearing; that means, $\dot{\gamma}_{yx}$is becoming 0. So, you are gradually increasing the $\dot{\gamma}_{yx}$ in order to do the experiment let us say. So, in gradually τ_{yx} is also increasing with a proportionality of a proportionality constant of μ right.

But moment you stop the shearing immediately shear rate will falls to 0. So, then when the shear rate falls to 0 immediately the shear stress will also falls to 0, that is what mean by if you stop shearing immediately stress will fall to 0 for a Newtonian fluid.

Then viscosities of same Newtonian fluid under different types of deformation are in simple proportion to one another whatever this experiment we have done it is shearing experiment. Other kind of experiment what we have? We have a kind of elongational deformation.

Let us say you take a fluid element and then you do the elongation in one direction right. So, then here deformation is different though it is a same fluid same Newtonian fluid. So, when you do the one dimensional, one direction unidirectional elongation, so then viscosity whatever is there that is indicated by μ_E let us say.

The same Newtonian fluid you took you take and then you do the elongation experiment in bidirectional like this in two direction let us say right. So, then whatever the viscosity is there it is going to be different because it is not a shearing experiment, it is an elongational experiment.

So, then whatever the viscosity is there that we call is let say μ_{EE}, like that if you do a planar elongation in all direction like this. Then the viscosity let us say whatever is there. So, it is a μ_{planar} because it is not a shearing experiment it is a deformation because of the elongation.

So, now different types of viscosities under different types of you know deformations you get in general. So, when you take the ratio between this viscosity to the shearing viscosity they are, they will be in a simple proportion to one another.

What does mean by simple proportion? This $\frac{\mu_E}{\mu}$ is going to be a constant for Newtonian fluid it is going to be 3 and then $\frac{\mu_{EE}}{\mu}$ that is the viscosity because of the bi-directional elongational experiment divided by the viscosity of the same fluid, but under shearing experiment if you do the ratio of these two then you get a constant value 6.

Similarly, the planar viscosity divided by the shearing viscosity is going to be another constant that is going to be 9 for a Newtonian fluid. So, these are the few important characteristics of the Newtonian fluids right.

So, now why we have written so many characteristics though we directly have a kind of definition τ_{yx} versus $\dot{\gamma}_{yx}$is passing through the origin and then that slope of that curve is a kind of constant mu does not change whatever the $\dot{\gamma}_{yx}$?

So, because this will provide all this enlisted characteristics will provide us to make a kind of basis for non-Newtonian fluids definition. Now since Newtonian fluid these many characteristics are there. So, whatever the characters, whichever the characteristic of a Newtonian fluid is not being obeyed by a fluid then we can call a, call that particular fluid as a kind of non-Newtonian fluid right.

Any fluid which does not obey one or more of these characteristics then we call them as a kind of non-Newtonian fluids. So, when we are saying that when a fluid does not obey one or more characteristics of these Newtonian characteristics then we call them a non-Newtonian fluids.

So; that means, more characteristics are been deviated so; that means, more number of types of non-Newtonian fluids are possible. Newtonian fluids we do not have categories we have only the low viscosity, high viscosity, intermediate viscosity these kind of different fluids are there, but the viscosity is constant that is what we are having.

But non-Newtonian fluids we can see we are going to enlist that we will be having so many types of non-Newtonian fluids are possible. So, once on the, one of the such kind of characterization that we can see for the non-Newtonian fluid here. So, let us say if you have a kind of non-Newtonian fluid where the normal stress difference is not 0 then that is one type of non-Newtonian fluid you can say.

Then let us say you have, you know another type of non-Newtonian fluids where the linear proportionality is not being maintained between the shear stress and then shear rate if you do not get a linear curve between shear stress and shear rate. So, then that could be that could be one kind of non-Newtonian fluid.

Another case you may have a linear type of curve you may have a linear type of curve here between shear stress and shear rate, but it may not pass through the origin you may have something like this; still linear, still linear here also and then viscosity that is constant right, but different value.

But it does not pass through the origin so; that means, there is a something like yield stress that is we are going to see in details. So, under such conditions also we can say viscosity is not changing, viscosity is not changing after crossing through after passing through this yield stress.

Once the yield stress is passed then the material is deforming so, but the viscosity is not changing after this τ_0, but before that it is having a large infinite effectively infinite viscosity. So, it is changing only two times initially it is having effectively large almost very large effectively infinite viscosity and after that it is having constant low viscosity.

So, that is also one type of non-Newtonian fluids right. Then you can have another type of non-Newtonian fluid. So, which may not be linear and then may not be passing through the origin. So, let us say not passing through the origin and after that you may have the non-linear curve like this that is possible. It may passing through the origin, but it may not, it may not be if it is not linear. So, then it may have curve like this or curve like this non-linear curves are there.

So, those are all possibilities of non-Newtonian fluids, different types of non-Newtonian fluids right. And then viscosity will not be independent of the shear rate for non-Newtonian fluids because as the shear rate increases the viscosity changes for non-Newtonian fluids because we have seen this τ_{yx} versus $\dot{\gamma}_{yx}$ mostly they are a they are non-linear and then even if they are having a kind of yield stress after that also they are having a kind of non-linearity stress.

So, then viscosity is affected by the shear rate. So, if you are doing the shearing experiment at the order of $10^{-2}s^{-1}$. So, then you may get the some apparent viscosity value if the same for the same fluid you take and then do the shearing experiments certain large value let us say $10^{2}s^{-1}$.

Then you may get the different viscosity value and then same fluid if you do the shearing let us say $10^{4}s^{-1}$shear rate then shearing if you do at $10^{4}s^{-1}$ then whatever the viscosity is there that apparent viscosity is going to be different. So; that means, for non-Newtonian fluids viscosity not necessarily be independent of the shear rate it depends on the shear rate right. So, that is another category of non-Newtonian fluid is possible right.

So, that is the reason for a non-Newtonian fluids we do not call simply viscosity we call apparent viscosity, but it changes we are going to see those details again. Then viscosity is independent of duration of shearing for the Newtonian fluid; that means, if a material if its viscosity is changing with the duration of shearing.

Let us say you are doing the shearing experiment at 10 power 2 second inverse when you are doing it for 10 minutes, when you are doing for 100 minutes, when you are doing for 1000 minutes you may get the different viscosities you may not get the same viscosity. Because the material rheology is dependent on the duration of shearing.

So, that could be one other type of non-Newtonian fluid ok. So, that is what you know for non-Newtonian fluids some of the non-Newtonian fluids the apparent viscosity may also depend on the duration of shearing.

And then stress not necessarily falls to 0 immediately after shearing is stopped right. So, that is another type of non-Newtonian fluid that is possible that we are going to see with a proper demonstration experiments. And then viscosities of you know some different type of deformation divided by the viscosity of the shearing deformation of a non-Newtonian fluid not necessarily they may have a constant values like 3, 6 and 9 like we have shown.

So, that is the reason we have recapitulated so many details of a Newtonian fluids. So, that from that information, from that Newtonian fluid information we can have a kind of a more characteristics of a non-Newtonian fluids that we can get ok. So, now what we do?

Before going into the details of non-Newtonian fluids we see a few more details of Newtonian fluids because in general it is misconception among several students, a material which is having high viscosity is a non-Newtonian fluid that kind of misconception is there right.

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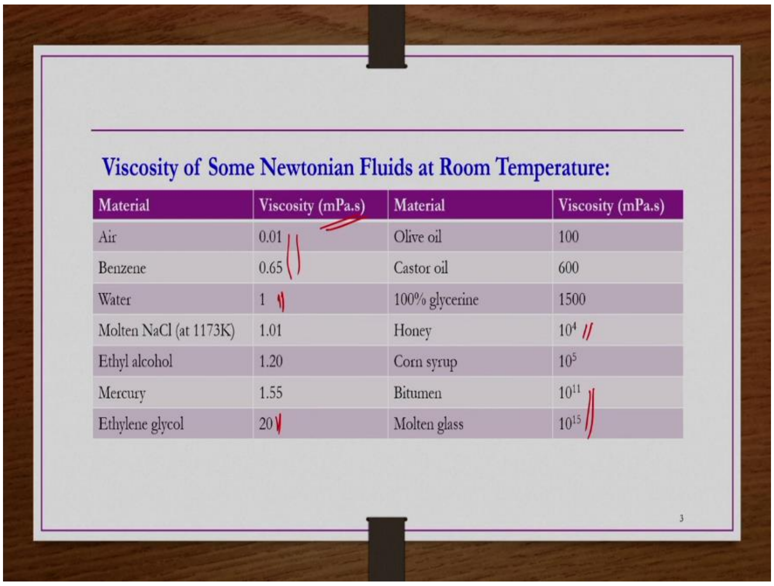

So, that is not true at all. So, if you see these examples here. See now this air, benzene, water, molten NaCl, ethyl alcohol, ethylene glycol, olive oil, honey, bitumen etcetera for all these materials viscosity is shown here, viscosity is shown here in mPa.s. You can see the material are having the viscosity as low as 0.01 mPa.s, 1 mPa.s, 20 mPa.s, 10^4 mPa.s, 10^{11}, 10^{15} mPa.s.

Such large amount of viscosities are possible, but they are still Newtonian fluid, but they are still Newtonian fluid. So, it is not necessary that any material having a large viscosity it is a non-Newtonian fluid such kind of misconception one should not have right. So, it is possible that even non-Newtonian fluids may have a very small viscosities very small apparent viscosities like you know 0.1 mPa.s etcetera that is also possible. Some non-Newtonian fluids are having high viscosity like you know order of 10^1, 10^2 mPa.s that is also possible.

So, from looking at the viscosities we cannot say where the material is you know Newtonian or non-Newtonian you need to have a proper information about the shear stress versus shear rate as well as the normal stress versus the shear rate information from that information only we can get a you know whether the material is Newtonian or non-Newtonian ok.

So, it is a just a kind of you know information. So, that we should not have a kind of means misconception that you know material having the high viscosities in non-Newtonian fluid it is not. Then coming to the non-Newtonian fluids we can have a kind of a definition now right. Because after having a kind of enough recapitulation of Newtonian fluids, now we are at a position that we can properly define non-Newtonian fluids ok.

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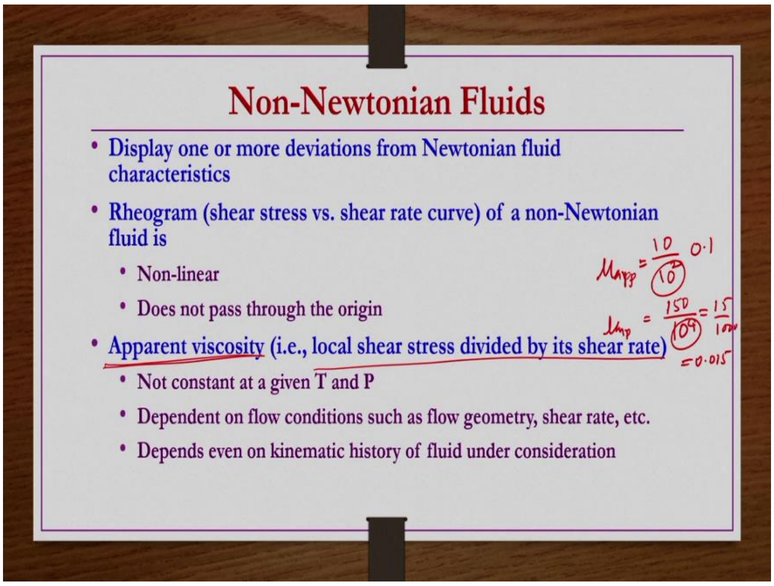

So, they display one or more deviation from Newtonian fluid characteristics as just now explained a few slides before. Then rheogram or shear stress versus shear rate curve of a non-Newtonian fluid it can be non-linear or it does not pass through the origin it is possible and then normal stress differences may not be 0 for non-Newtonian fluids.

The apparent viscosity as I mentioned we will not call viscosity for non-Newtonian fluids we call it apparent viscosity because we realize that the viscosity is going to change with the shear rate for non-Newtonian fluids in general right. So, that is the reason viscosity whatever the apparent viscosity is there that local shear stress divided by its shear rate. So, let us say if you are doing shearing experiment at order of $10^{-2}\ s^{-1}$.

So, whatever the shear stress is there that shear stress let us say you get 1000; 1000 let us say shear stress you get a 10. So, $\frac{10}{10^2}\ s^{-1}$. So, this should be whatever 0.1 should be the apparent viscosity of this material right So, let us say if you are doing the shearing experiment at order of $10^4\ s^{-1}$ and then corresponding shear stress is let us say 150. So, then μ_{app} here should be $\frac{15}{1000}$. So, it is 0.015.

So, now see the at same material, but you are doing shearing experiment at different shear rates right then you are getting the local shear stress divided by the shear rate at which you are doing the shearing experiment that ratio whatever is there we call we are finding it is not a constant value it is changing. So, that is the reason we call it as a kind of apparent viscosity right.

So, this apparent viscosity whatever is there not constant even at constant temperature and pressure. Even at constant temperature and pressure the apparent viscosity not constant for a non-Newtonian fluid. And then dependent on the flow conditions such as the flow geometry, shear rate etcetera.

Then it even depends on the kinematic history of the fluid under consideration we are going to see all these details any way. Now what we see? We see a few examples of non-Newtonian fluids. Non-Newtonian fluids almost all ubiquities in all processing industries chemical or material processing industries. Any chemical or material processing industry you see one or other fluids or you know displaying some kind of one or other kind of a non-Newtonian fluid, non-Newtonian characteristic right. So, we see a few examples we just enlist here.

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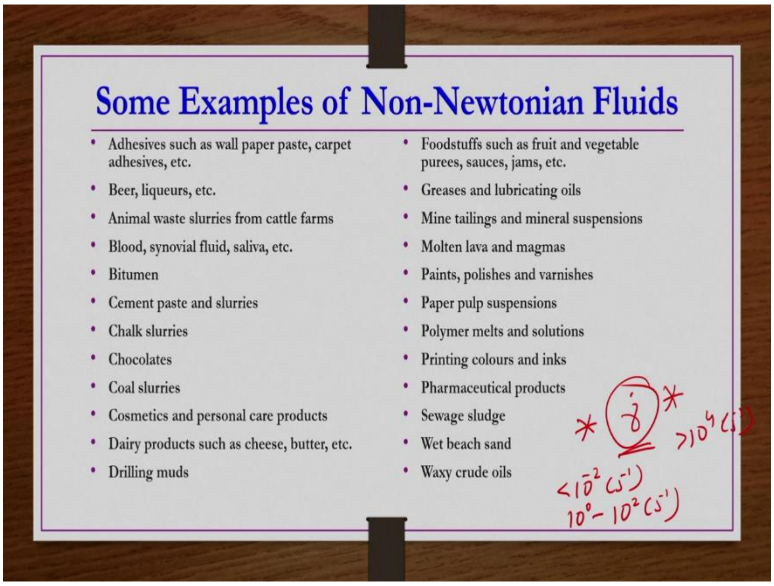

See adhesives, liquors, animal waste slurries, blood, synovial fluid, bitumen, cement paste, chalk slurries, chocolates, coal slurries, cosmetics, personal care products, dairy products, drilling muds, food stuffs, grease, mine tailings and mineral suspensions, molten lava, paints, polishes, polymer melts, printing colours, pharmaceuticals products, sewage sludge, wet beach sand, waxy crude oil.

See now pharmaceuticals, petroleum, chemical, beverage industries, food industries, cosmetic industries, you know dairy industries; almost all industries are covered here and then one or other kind of material have been listed here. And then these materials are having one or other kind of non-Newtonian characteristics at a specified shear rate, at a specified shear rate.

So, these are the some examples of non-Newtonian fluids. So, remember I will be recapitulating this several times in at least initial 2 to 3 weeks, whenever you call you talk about the non-Newtonian fluids you should ask what is the range of $\dot{\gamma}$ what is the range of shear rate.

Because soon you are going to find out under certain range of $\dot{\gamma}$ the material may be having one characteristic. Under other range of characteristics let us say this range it may be having different characteristics and then another range of large shear rate it may be having entirely different characteristics.

So, one given single material it may be having a Newtonian behaviour at certain range of shear rate it, may be having a one type of non-Newtonian behaviour in certain range of shear rate. In another range of shear rate it may be having all together entirely different type of non-Newtonian behaviour it is quite possible.

So, what we understand? The rheologically non-Newtonian fluids are very complex. So, then you when you talk about the non-Newtonian fluids you have to specify what is this shear rate, what is this shear rate under which range you wanted to know. Let us say you have a material we are going to see examples. So, you are processing you know you are handling at chemical process industry where the shear rate whatever the $\frac{dv_x}{dy}$ or $\frac{v}{y}$ in general crude way we take $\frac{v}{d}$ something like that.

So, these ratios you know if they are in the small range. So, then it is possible that material may be Newtonian. So, you do not need to worry about the characteristics of non-Newtonian behaviour their model, their influence on the performance of the processing unit that all you do not need to consider, even though the material may be having non Newtonian characteristics. It will some other different shear rate.

So, that is the advantage of this course where that we are going to see that you know under what range non-Newtonian characteristics are important that we can identify and then if required then only we can we need to make a alternative adjustment either in the design or operating conditions of the material processing units ok.

So, whenever we talk about non-Newtonian fluids we should ask what is the range of shear rate because the non-Newtonian characteristic may not be existing for all range of shear rate for the same material. Same material may be having certain kind of characteristics at certain range of shear rate and then it may be having different types of characteristics at different range of shear rate ok. So, this is very essential.

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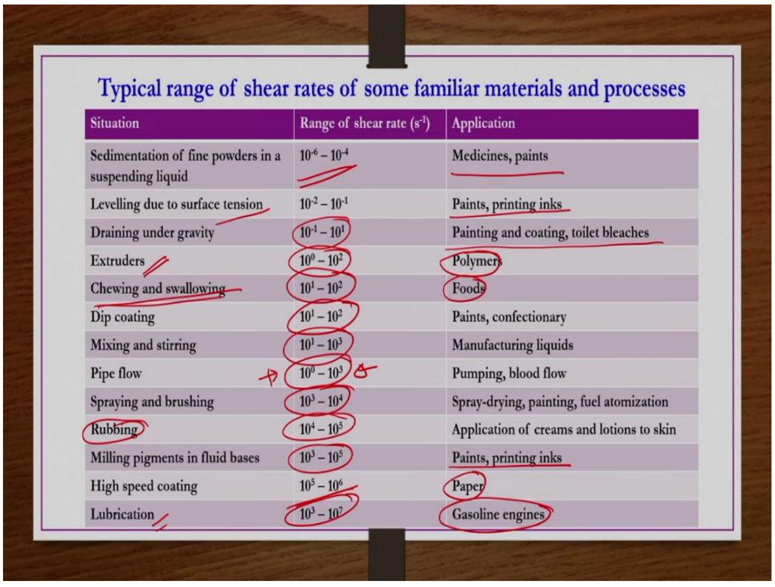
Typical range of shear rates of some familiar materials and processes

Situation	Range of shear rate (s^{-1})	Application
Sedimentation of fine powders in a suspending liquid	$10^{-6} – 10^{-4}$	Medicines, paints
Levelling due to surface tension	$10^{-2} – 10^{-1}$	Paints, printing inks
Draining under gravity	$10^{-1} – 10^{1}$	Painting and coating, toilet bleaches
Extruders	$10^{0} – 10^{2}$	Polymers
Chewing and swallowing	$10^{1} – 10^{2}$	Foods
Dip coating	$10^{1} – 10^{2}$	Paints, confectionary
Mixing and stirring	$10^{1} – 10^{3}$	Manufacturing liquids
Pipe flow	$10^{0} – 10^{3}$	Pumping, blood flow
Spraying and brushing	$10^{3} – 10^{4}$	Spray-drying, painting, fuel atomization
Rubbing	$10^{4} – 10^{5}$	Application of creams and lotions to skin
Milling pigments in fluid bases	$10^{3} – 10^{5}$	Paints, printing inks
High speed coating	$10^{5} – 10^{6}$	Paper
Lubrication	$10^{3} – 10^{7}$	Gasoline engines

So, now we can see a few you know situation familiar materials and then situations where you know we need to know typical range of shear rate; typical range of shear rate we need to know in general right. So, that is what we are going to see now. In general what happens you know? We have you know different types of operations right whether Newtonian or non-Newtonian material whatever it is say. So, certain force will be applying and then certain shear rate would be there.

So, it is essential to have a kind of a-priori information if not the exactly rough information for a given application what kind of what range of shear rate may be existing right. So, that we see now. So, now if you have a situation like sedimentation of fine powders in suspending liquid. So, such kind of applications we see in medicines and paints and then shear rate is very small, order of 10^{-6} to $10^{-4} s^{-1}$.

We have a leveling due to surface tension that kind of situation in paints, printing inks applications. So, there shear rate is order of $10^{-2}$to 10^{-1} some other paints and coating, toilet bleaches applications. So, there the shear rate because of the draining under gravity is order of 10^{-1} to $10^{1} s^{-1}$.

Extruders are very common in polymer industries. So, wherever we have the extrusion applications in polymer industries. So, in general the shear rate under such conditions is order of 10^{0} to 10^{2} s^{-1}.

Several times we chew and then swallow different types of food materials. So, that is application in food industry. So, then chewing and then swallowing that thing in general we do, the shear rate is in general order of 10^{1} to 10^{2} s^{-1}. Then paints, confectionaries sometimes you do the deep cutting let us say corn syrup such let us say corns are there cornflakes are there you wanted to do some kind of coating using the honey or something like that.

So, that you can have the honey flavor as well in the food industries. So, then dip coating sometimes is used and then spray coating is also done in some other applications let us say wherever you have the dip coating. So, then shear rate is order of 10^{1} to 10^{2} s^{-1}. Likewise in mixing and stirring which is very common in process industry 10^{1} to 10^{3} s^{-1}pipe flow 10^{0} to 10^{3} s^{-1}.

Spray and brushing like in spray drying, painting, fuel atomization there also we have this spraying. So, there range of shear rate is 10^{3} to 10^{4} s^{-1}then in general creams and lotions that we apply to the skin right. So, by rubbing kind of actions. So, there this shear rate is very high as usually 10^{4} to 10^{5} s^{-1} that is the reason in general when we apply this lotions or creams to our skin our palms are getting warmed up slightly because the shear rate is very high.

We are applying high shear rates then paints, printing inks etcetera. So, milling pigments in fluid bases up to $10^5\ s^{-1}$. The paper; in general paper coating has been done in for different layers like in a glassy layers or something like that where high speed coating is done.

So, then the shear stress even high 10^6 order of $10^6\ s^{-1}$ etcetera. And then in gasoline engines whatever the lubrication actions are there. So, there under such conditions shear rate can be even high order of $10^7\ s^{-1}$ that is possible.

So, now we see depending on the applications depending on the situation the shear rate changes right let us say pipe flow you have taken and then shear rate is in this range. So, the material is non-Newtonian, but under this range of shear rate if the characteristic the non-Newtonian effect is how much important that you have to see.

If it is less so, then you do not need to worry, if it is more then we have to consider the non-Newtonian behaviour in the design equations and all that. So, now, we see a classification of non-Newtonian fluids.

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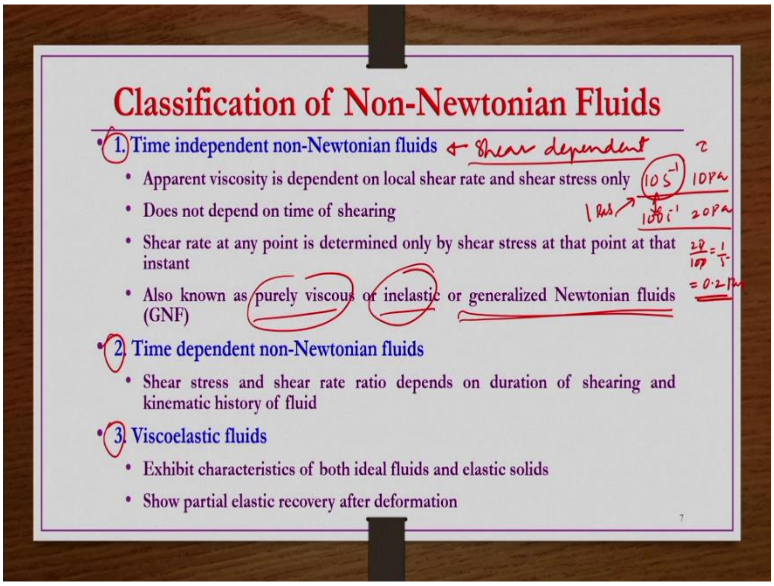

Non-Newtonian fluids; we have seen different types of possibilities have seen like we have a enlisted several n number of types of characteristics of Newtonian fluids not n, if not n number around 6 to 8; in case of a Newtonian fluids we had around 6 to 8 characteristics of a Newtonian fluids from those characteristics.

So, then we can have a kind of we can group some of the characteristics and then we have a kind categorize the materials whichever does not follow though that particular group of Newtonian characteristics is one type of non-Newtonian fluid like that.

That way if we do we can have a kind of a classification of non-Newtonian fluids. Because we have already seen that one single material may be having different characteristics and then the classification may become very difficult right.

So, different types of classifications are also possible, but whatever we are discussing here that is most general and mostly accepted classification of non-Newtonian fluids. So, one is with respect to the shear rate, another one is with respect to the duration of shearing, another one is the any you know memory that material is having based on those kind of characteristics we are going to have a classification on this non Newtonian fluids.

So, we take about the shear rate dependent non-Newtonian fluids. Time independent non-Newtonian fluids, but they are dependent on the shear rate, but they are dependent on the shear rate. So, these materials are you know their apparent viscosities function of shear rate, but it is not function of the duration of shearing. That is time independent non-Newtonian fluid.

Then time dependent non-Newtonian fluids. So, these materials are in addition to the depending on the shear rate it may also depend on the duration of shearing also it may also depend on the duration of shearing also. So, those materials are known as the time dependent non-Newtonian fluids.

And then some materials having both elastic and then viscous nature under different situations. So, then those materials are known as the viscoelastic fluids right. So, broadly these three different way we can classify the non-Newtonian fluids right. If you see some more details about these things as I mentioned. So, time independent non-Newtonian fluids apparent viscosity is dependent on the local shear rate and shear stress only right.

So, whatever the apparent viscosity that is there that depends on the local shear rate only and then shear stress. So, that apparent viscosity it changes with the shear rate information with the value of the shear rate ok. But it does not change with the duration of shearing ok; that is the other characteristic. Does not depend on the time of shearing, but it depends on the range of shear rate ok.

So, this time independent non-Newtonian fluids the other way you call them as a shear dependent non-Newtonian fluids. See the other name that we can call for this fluids is, they are independent of duration of shear, but shear dependent on the shear. Shear dependent non-Newtonian fluids.

And then shear rate at any point is determined only by shear stress at that point at that instant only as I just mentioned ok. So, that is let us say if you have a you know this $\dot{\gamma}$ is 10 s^{-1} $\dot{\gamma}$ is 100 s^{-1}. So, the corresponding shear stress whatever is there that is let us say in the first case is 10 pascals and the second one is just 20 pascals. So, in apparent viscosity here first case $\frac{10}{10}$ is 1 Pascal second right.

In the second case $\frac{20}{100}$ equals to 1 by 5. So, then what we have? Point 10 so, 0.2. You have 0.2 pascal second whereas, in the first case the apparent viscosity is 1 pascal second here 0.2 pascal second apparent viscosity is decreased when you change the shear rate or when you increase the shear rate from 10 to 100 s^{-1}.

So, that kind of shear depended behaviour these materials may be having. So, that is the reason they are known they are also known as the shear dependent non-Newtonian fluids also known as the time independent non-Newtonian fluids because they are dependent on the shear rate, but it they do not depend on the duration of shearing.

Then they are also known as the purely viscous or inelastic or generalized Newtonian fluids GNF generalized Newtonian fluids; why? Because under certain limiting conditions under certain limiting conditions of shear rate this materials in general they reduce to, they reduce to Newtonian behaviour or they show Newtonian behaviour under certain limiting conditions.

So, that is the reason these materials are also known as the generalized Newtonian fluids purely viscous inelastic or generalized Newtonian fluids this is the other name for this class of a non-Newtonian fluid right. So, that is the 1st class of this materials see, 2nd class of non-Newtonian fluids is the time dependent non-Newtonian fluids. So, they are dependent on the duration of shearing as well the apparent viscosity is also dependent on the duration of shearing ok.

Shear stress and shear rate ratio depends on duration of shearing and kinematic history of the fluid as well. So, this is the like you know some materials they become you know thicker in little time whereas, the some material you know they become very thinner with respect to the time of shearing. So; that means, apparent viscosity is changing. So, that is they dependent on this material the apparent viscosity depends on the duration of shearing as well as the kinematic history of the fluid as well.

So, we are going to see example with a demonstration experiment of a few examples as well to realize how it is, how we feel that whether this a material is having a kind of time dependent behaviour time independent behaviour all that we are going to see a few demonstration experiments also in the subsequent lectures anyway.

Then viscoelastic fluids these materials will display viscous behaviour under certain range of shear rate and then they also display elastic nature under certain range of a shear rate. So, that is the reason these materials are known as the viscoelastic materials. So, that is exhibit characteristics of both ideal fluids and then elastic solids as well ok.

And then they also show partial elastic recovery after deformation. Elastic material we know when you apply a external force so they go some kind of deformation, but when you remove the force applied force then the material try to regain it is initial shape some material regain their initial shape completely. So, they are perfectly elastic.

Some material regain their initial shape only partially right. So, they are you know partial recovery state. So, these non-Newtonian fluids they may have a such kind of memory to recover. So, that they have a recovery possibly partial the elastic recovery is possible for this kind of materials. So, these are known as the viscoelastic fluids.

Rather fluids we can call them viscoelastic materials because under certain conditions they are almost like a solids or semi solids ok. So, broadly what we have? We have a three categories of a non-Newtonian fluids. The 1st category is the time independent non-Newtonian fluid also known as the shear dependent non-Newtonian fluid. Then 2nd category is the time dependent non-Newtonian fluids where the apparent viscosity of the material not only depends on the shear rate, but also it depends on the duration of the shearing.

And then 3rd category is the material, which is also having elastic behaviour partial velocity elastic behaviour in addition to the viscous flow behaviour viscous deformation behaviour right. So, the references for this particular lecture are provided here.

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Most of these details provided in this particular lecture are have been taken from this book Non-Newtonian Flow and Applied Rheology by Chhabra and Richardson. The other reference is Rheology: Principles, Measurements, and Applications by Macosko it is also a very good reference. In fact, these are the two books that we are going to follow in most of the coming lecture in at least another 3 to 4 weeks.

Additional references you know Transport Phenomena by Bird Stewart and Lightfoot. That is also an excellent book for some of the transport phenomena related problem that we are going to discuss you know after a few weeks.

Then some reference books are Rheology Essentials of Cosmetics and Food Emulsions by Brummer. And then Rheology for Chemist: An Introduction by Goodwin and then Hughes. Then Rheology of Fluid and Semisolid Foods: Principles and Applications by Rao.

Thank you.