Rheology of Complex Materials
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Lecture - 02
Flow phenomena in complex materials and microstructure

So what we saw in the earlier lecture was how shear flow, induced shear as well as normal stresses in the Non-Newtonian fluids, and how at low and high shear rate the colloidal particle microstructure could be useful in explaining the shear thinning phenomena, as well as molecular stretching in case of a macro molecular system could be useful in explaining the rod climbing as well as extruded swell phenomena.

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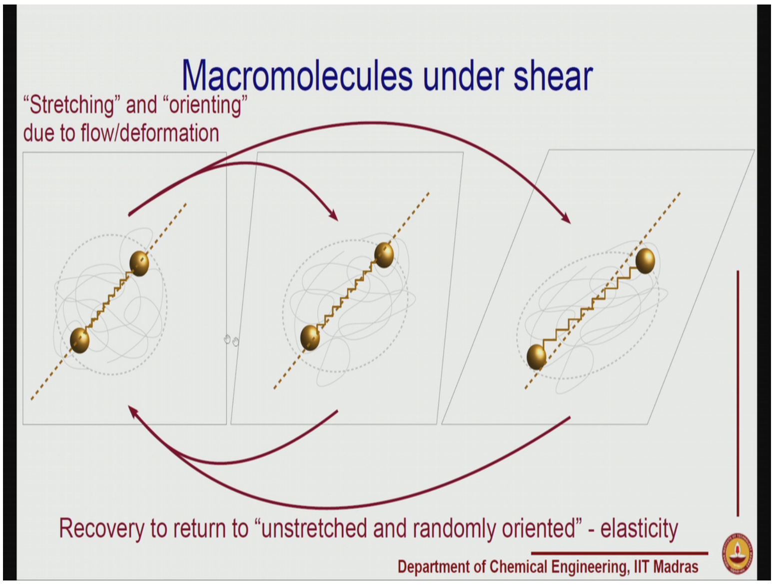

So, now going further we will again look at few additional phenomena and just to again remind ourselves this macro molecular picture at the mechanical analog scale you have stretching an orientation in flow, and in due to this stretching and orientation there is a tendency whenever flow is stopped the tendency of the speed to go back to "unstretched and randomly oriented" and bead and the dumbbell. And therefore, there is always an elasticity associated with these macro molecular solutions.

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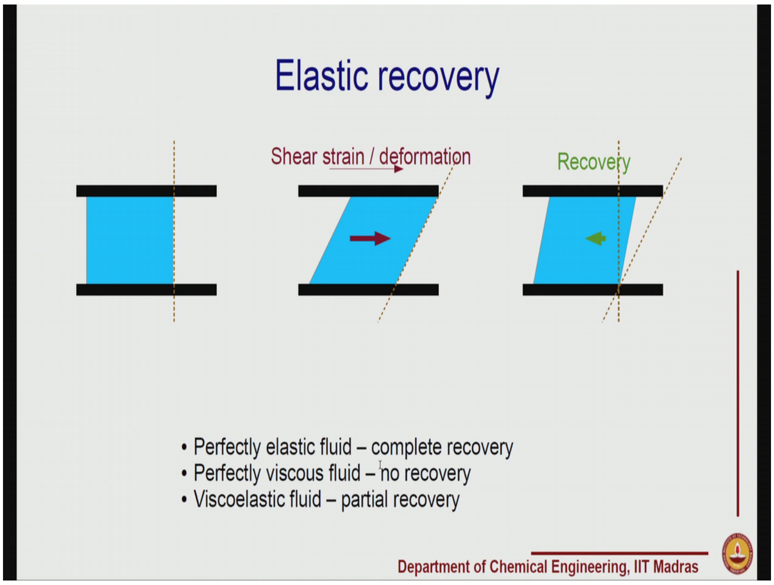

Now, let us look at the phenomena of elastic recovery, which is observed if we take a fluid between 2 plates and let us say we impose a shear strain, which implies that I just move this top plate to with a small distance and so therefore, the overall fluid would also move and then it would acquire a new shape because of this deformation and the fluid is getting deformed and of course, the measure of this deformation is this angle by which the fluid has deformed which is the simple shear deformation that we learn.

Now, if we let go whatever once the deformation has been achieved then what happens is in case of solid the overall material would again come back and acquire the same shape that it at earlier. And therefore, the material would switch back and forth between undeformed and deformed configuration when we apply constant deformation on it. Whenever we apply a constant deformation it will become deformed, when we release the deformation when we release the force that was used for making the deformation possible the material will come back to it is original state and that is, what is elasticity of the solid material.

Now, since we have taken a fluid material in case of a Newtonian fluid what would happen is the fluid would just remain wherever it is, because in case of Newtonian fluid there is no recovery possible at all. In fact, the Newtonian fluid is an example of a perfectly dissipative or a perfectly viscous system, in which case the mechanical energy that was input through this top plate gets dissipated in the fluid and therefore, there is no elastic recovery at all. On the other hand the colloidal dispersions which is Non-Newtonian or a macro molecular melt which is Non-Newtonian there will be a partial recovery. In which case the deformation will be recovered to small extent and to how much extent will depend on the amount of elastic recovery that the fluid can have.

So, therefore, there is a recovery possible in the materials which we are going to study in this course and again just to emphasize the initial configuration where there was no deformation is given by this, when you have deformation then the angle is given by this line and of course, the partial recovery implies that the fluid is somewhere in between. It does not come back completely to this line which would be the undeformed line it does not stay there which would imply that it remains like a viscous fluid. So, if the fluid remains in this orientation with this amount of shear deformation then it is a viscous fluid and if the fluid comes back completely to this deformation, which means it is 0 deformation undeformed configuration then it would be a perfect solid.

So, therefore, a perfectly elastic fluid will have a complete recovery while perfectly viscous fluid will have no recovery and viscoelastic fluid which is what we are going to study in this course will have always partial recovery. And again this recovery is associated with the stretching and unstretching or orientation and going back to random configuration of macromolecules at the microscopic scale.

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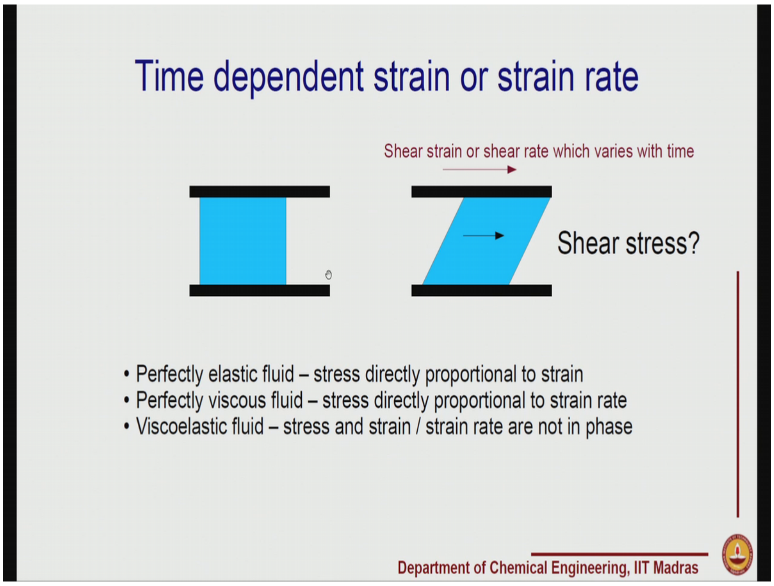

The other phenomena which quite often will be very useful to us is to look at what happens when we apply a time dependent strain or strain rate on the material. So, a time dependent strain or strain rate can be applied when we actually move this top plate with certain time dependent velocity.

So, therefore, the shear strain or shear rate which varies can be applied on the top plate and most often what we will end up looking at in terms of time dependent quantities may be a sinusoidal function.

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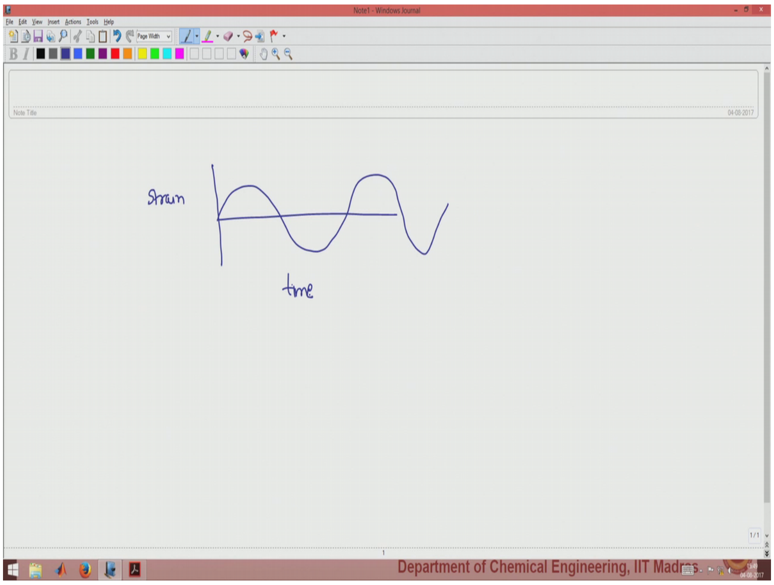

So, therefore, what we have is basically let us say a strain which is being applied as a function of time. So, we may have a sinusoidal strain. So, in this case the strain goes through maximum and minimum and we would look at response of the material to so this is basically strain as a function of time. And the idea is to look at what happens to the shear stress, when we have what happens to the shear stress when we have this material being applied to a sinusoidal strain or shear rate.

So, what we will see is in cases with perfectly elastic fluid we will have stress directly proportional to strain this is similar to what we this is due to let us say Hookean nature of the Fluid Hookes law is where stress is directly proportional to strain and therefore, wherever stress is maximum strain would be maximum.

So, in other words we can also say that stress and strain are in phase, if we look at perfectly viscous fluid then stress directly is proportional to strain rate and since strain rate and strain are out of phase, what we can see is stress will be out of phase with respect to strain. And of course, in viscoelastic fluid what we will have is stress and strain and all strain rates will not be in phase nor will be completely out of phase.

So, there will be a phase which is neither 0 nor 90 and in fact, will be an indicator of the relative contributions of elasticity and viscous nature in these fluids. So, again going back to the colloidal system that we thought of where there were clusters and network of clusters, what we can see is when we shear the system at as a continuous time, what happens is the clusters also will get adjusted based on the deformation being imposed. And therefore, the overall property of the fluid that we observe will depend on what is the magnitude of the shear strain amplitude or of the shear rate which is being imposed.

So, in all these cases it is always helpful to go back and look at the microstructure of the material.

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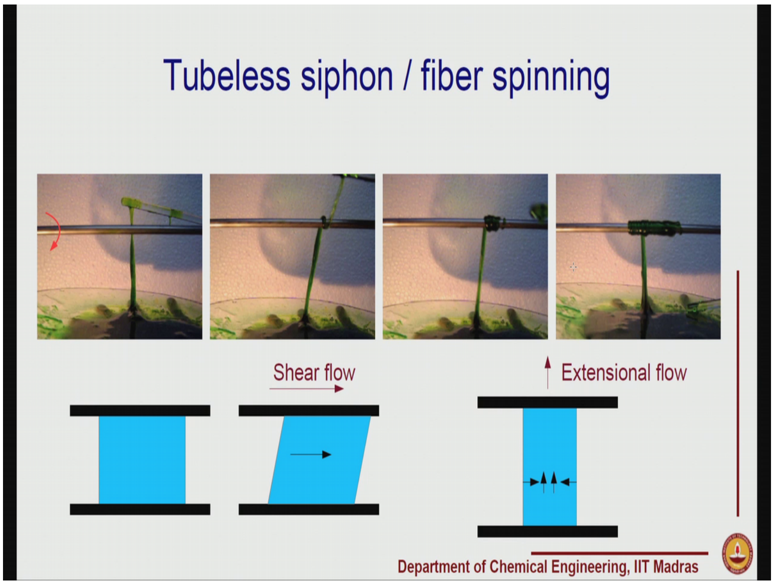

One other example where it is very useful to see the qualitative difference that is observed between Non-Newtonian fluid and Newtonian fluid is this where we can actually use to extract the fiber out of a Non-Newtonian fluid. So, this green fluid here is basically a poly acrylamide solution in which I can dip a rod and when I pull the rod I can pull a fiber out and that fiber if I now put it on a rod which is rotating what happens is the fiber starts rotating and this is how fiber spinning is actually done. We basically extrude the fluid from a small opening and then we take it up on a roller and we roll it and during this process we stretch the fluid filament.

So, what we have seen earlier. So, far were all examples of shear flow, where we took the fluid between 2 plates and then we may make the subjected the fluid to shear deformation by imposing a shear flow. Now in this fiber spinning operation when the filament is getting stretched here what we have is analogous situation where we take fluid between 2 plates and then we have the plates being pulled apart. So, that the fluid actually gets stretched if you see in case of shear flow what is happening is fluid layers are moving horizontally in this case and therefore, you have lamina or sheets of fluids which are experiencing shear against each other and they are flowing in the direction of the flow.

In this case what we have is fluid will radially come in while it will in the axial direction it will move apart because the plates themselves are being stretched apart. So, in this case also when we have the filament what will happen is the diameter of the filament will start becoming smaller and smaller, which means there is a radially inward flow and the height or the length of the filament will start becoming more and more because there is a stretching in that direction. So, the faster I rotate this rod the more stretching I can achieve if this rod rotates very slowly then the stretching achieved will be very low.

So, in these kind of cases what we have are called extensional flow and it is helpful also to think of the shear flow and extensional flow being present even in our day to day life and for example, some of you may have noticed in the kitchen sugar solution being made sugar syrup being made. It is important ingredient for most of the sweets that we make and this sugar syrup when it is made actually there is a rheological testing that is going on to try to measure it is properties. Why this is important this in case of sugar solution being made the concentration of sugar is very important as later on it will decide not only the consistency of the sweet, but also the taste of it.

So, the sugar as the sugar concentration increases the network in which sugar molecules are attached to each other through hydrogen bonding networks that also keeps on changing and because of this network present just like we saw the colloidal particle network earlier the flow properties of the fluid change. So, therefore, if this sugar solution to be examined and what is the concentration reached, what we do in kitchen actually is do a rheological test and that rheological test is an indicator of what may be the sugar structure and therefore, it is an indicator of what may be the sugar concentration.

So, if you remember what is done is actually when the sugar is stirred we sometimes we will take the spoon and then try to see how the flow rate how it drops. So, that sort of gives us an indication of what may be the viscosity of it similarly we can take the sugar solution on our finger and do this. So, this is by doing some the we are exactly doing the shear flow, because we are taking the fluid between 2 fingers and actually rubbing it. So, that it is imposed on shear flow. So, therefore, in the kitchen what we are doing while trying to make this sugar syrup we are trying to look at it is shear properties, but those of you who have observed closely may have also seen that. In fact, sugar is taken and we. In fact, perform extensional flow on it.

What we do is we take the sugar solution and in fact, do this to see if there is single wire formed or 2 wires formed and again depending on the elasticity of the sugar network, depending on the hydrogen bonding network which is present in the solution, which of course, relates to the concentration of the sugar whether it is one fiber formed or 2 fibers will be formed.

So, in fact, in kitchen itself in a qualitative manner we do both shear flow as well as extensional flow to try to examine what is the concentration and what is the molecular structure that the sugar solution has. So, naturally even in case of complex fluids complex materials, which are used in several engineering applications we tend to use both shear flow as well as extensional flow to try to characterize the material. More often than not we may have combinations of shear flow and extensional flow in an application, but generally to characterize it in a laboratory; we try to either impose shear flow and try to understand the material flow material behavior very well or we impose an extensional flow and then again try to characterize and understand the material very well.

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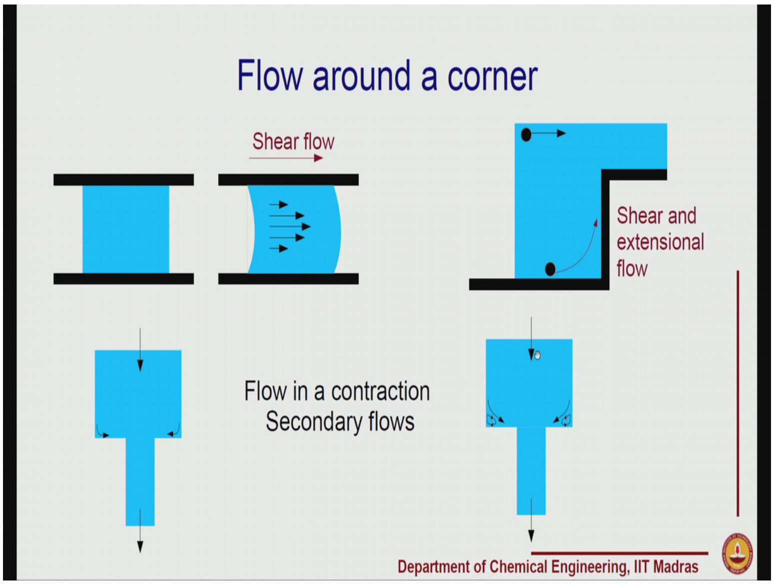

So, let us see how for example, this extension and shear combination may be there during a practical example on the left what we have is basically fluid between a pipe and because there is a pressure gradient between one end of the pipe and another end of the pipe, what we have is usually a parabolic velocity profile set, where the center of the fluid moves faster and the fluid at the periphery does not move at all and we have, basically in this case sheets of fluids which are moving and fluid sheets which are closer to the center move faster, while sheets which are progressively towards the walls move slower and slower. Now in this case all fluid elements are basically subjected to shear alone.

Now, let us say if in the same flow if somewhere down the line the diameter of the pipe changes. So, we encounter a situation which is given here. So, if let us say the step change is there a fluid element which is very far away is again just going to encounter pretty much shear flow and it will be part of those sheets it is neighboring sheets which are all predominantly experiencing shear flow; however, a fluid element which is much closer to this change it will when it goes around this corner it will experience not only shear, but also extensional flow.

In this case what happens is the velocity of the fluid keeps on changing at is as it moves along and therefore, later on in the course we will see that during these corner flows the kinematics of the fluid flow will have both shear and extensional components. Therefore, if one is interested in knowing the flow let us say or in a contraction we need to be able to describe both shear and extensional behavior of the fluid. If it is a Newtonian fluid then what happens is in both cases the response is characterized by the same parameter viscosity and in case of Non-Newtonian fluids we will see that if you characterize the material in shear flow alone 2 materials which are very similar in shear flow may end up giving very different response in extensional flow.

So, in other words if we have this 2 fluids which have same viscosity flowing through here the amount of extension which is experienced by the fluid, which is classic flowing closer to the change in the geometry may feel actually remarkably different extensional strains and strain rates. This is very relevant whenever we have such change in geometries, most of engineering situations we will have contractions and expansion joints; where basically diameter of one section is different than the diameter of the other section. And let us say if we are looking at low Reynolds number flows then what we have is a fluid which is flowing predominantly in shear, because the diameter of the overall cross section here is constant when it goes around and since the Reynolds number is very low, fluid actually follows pretty much the geometry and then again the flow is predominantly shear.

While in this case because of the extensional attachments actually secondary flow patterns break out. So, what we have our dead zones which arise in this flow. So, these kind of dead zones are also very of great practical interest because it they should be avoided. So, when let us say a car part is being manufactured with some part of the car being a small thickness and some other part being higher thickness then in a mold we will have such contraction, where the polymer which is molten will be forced into these kinds of gaps and then it will go through this contraction. And what will happen is because of these red dead zones the melt here will solidify at a completely different rate compared to somewhere else and the amount the kind of properties that this ends have may be very different compared to the rest of the things. And they may end up being the weaker spots of the overall part and these weak spots are problematic from the point of view of overall performance later on.

So, in general when we are doing processing of polymeric melts we have to be very carefully looking at such flows, which happen in a realistic component engineering component. What happens is polymeric molecules which are all randomly oriented here because of this contraction they start becoming stretched and because of the flow around the corner they again get stretched because of extensional components. So, therefore, the response their response is very different compared to what you would expect for a Newtonian fluid.

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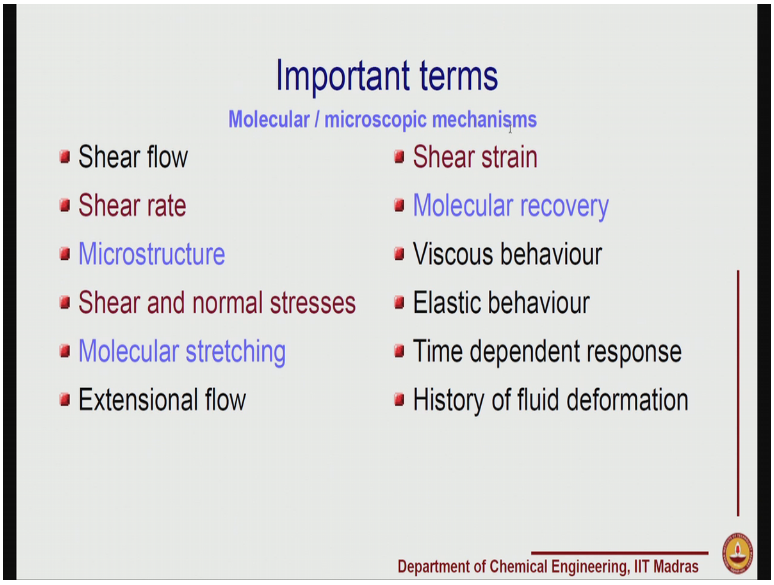

So, the important terms that we have looked at are in terms in addition to shear flow related things, we looked at also the extensional flow and we also tried to characterize the viscous and elastic response characterization terms in terms of viscous and elastic responses and we also saw in addition to shear flow and the extensional flow. We could also define the type of deformation that is being given to the material and how history of fluid deformation is important. In the sense that- where did the fluid, what kind of deformation was seen by the fluid earlier and what is seen in the present time?

So, just to again reemphasize what we have was one set of parameters which we can call the kinematics or kinetic variables, by kinematic variable we mean what specifies the position of material particles in the continuum or also they specify the deformation and deformation rates. So, shear rates and shear strains are quantifications of kinematics of material the stresses on the other hand are kinetic variable. So, to describe the rheology of complex materials we need inter relation of these variables so how kinematical variables are related to kinetic variables.

The other important feature which is very important in order for us to explain the flow phenomena in these materials are molecular microscopic mechanisms. So, in case of colloidal system for example, we saw clustering of particles which is an important mechanism network formation which might lead to the behavior that we see in practical terms. Similarly in macromolecular case we saw stretching and recovery as being very important in terms of understanding the overall phenomena.

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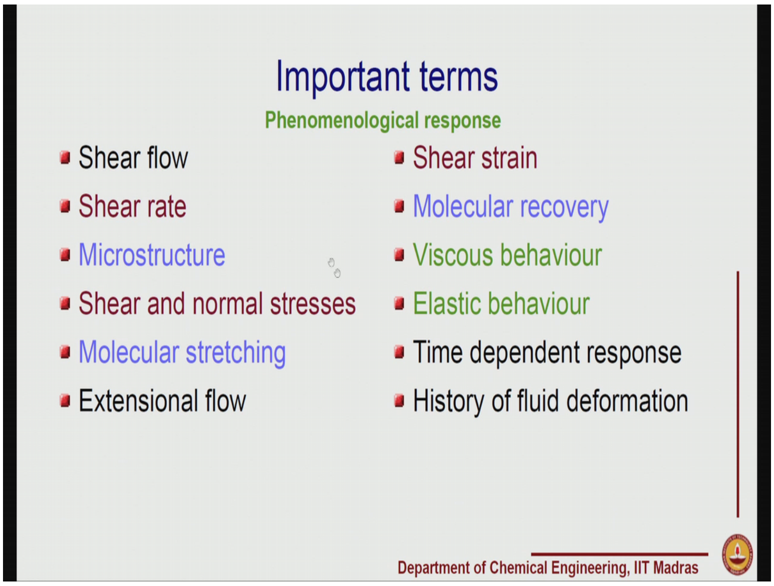

We also saw that there are phenomenological responses and we characterized responses if it was in phase or out of phase we said it is viscous or elastic if it recovered completely or recovered partially.

So, all of these phenomena logically can be described in terms of viscous and elastic or viscoelastic responses and it is important for us to note these phenomenological responses. So, that we can arrive at an appropriate understanding in terms of whether viscous behavior dominates or elastic behavior dominates and to what extent.

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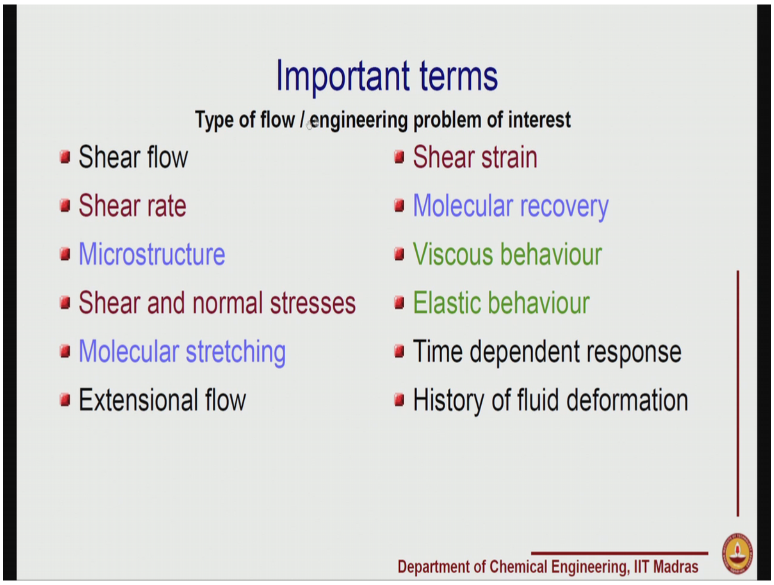

And finally, we have of course, the type of flow or whatever is the engineering problem of interest, which decides what type of flows are important, whether shear flow is important, whether extensional flow is important, whether we need to look at time dependent response, whether we will need to look at what was the history of deformation that was imposed in addition to just current deformation that the fluid is undergoing.

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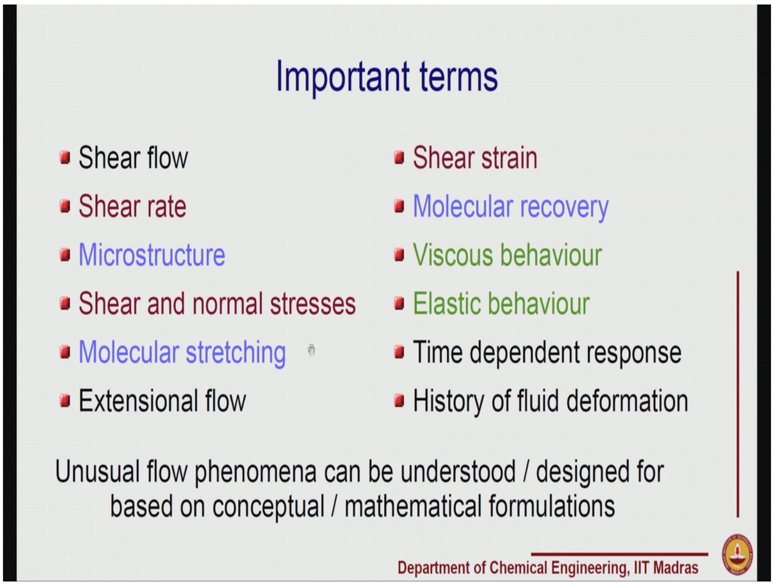

So, all these put together are actually important if we have to understand the unusual flow phenomena such as rod climbing or secondary flows in Non-Newtonian fluids and therefore, in this course we will look at interplay of all of these in terms of how do we use these to explain the qualitative as well as quantitative behavior of the Non-Newtonian fluids. And these terms will be useful for us to not only form the conceptual framework in which to understand the behavior, but it will be also useful in for us to actually form mathematical governing equations so that we can describe their behavior far more quantitatively.

So, with this what we have done in the last 2 lectures is look at the unusual flow phenomena try to relate it to the microstructure and in turn see what are the broad variables which might be of interest so that these variables; we can when we learn about these variables. Later on in the course we always come back to this to see what was the motivation or what was the relevance from which these terms arise.