Rheology of Complex Materials
Prof. Abhijit P Deshpande
Department of Chemical Engineering
Indian Institute of Technology, Madras

Lecture - 10
Stress and Strain rate

What we have done in the previous couple of lectures is to get used to the idea of stress and strain rate.

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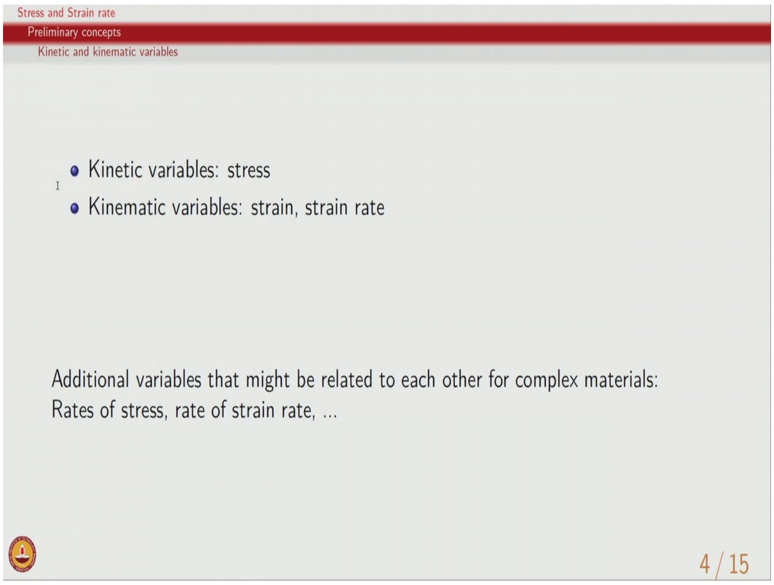

So, to begin with what I will do is I will just go through quickly with some of the main ideas and which are related to that the fact that there are contact forces and body forces and pressure and stress are example of the contact forces. And of course, gravity is the only other body force that we will use for our course. Though for electro rheological fluids or magneto rheological fluids clearly electric field or magnetic field will also be involved as a body force.

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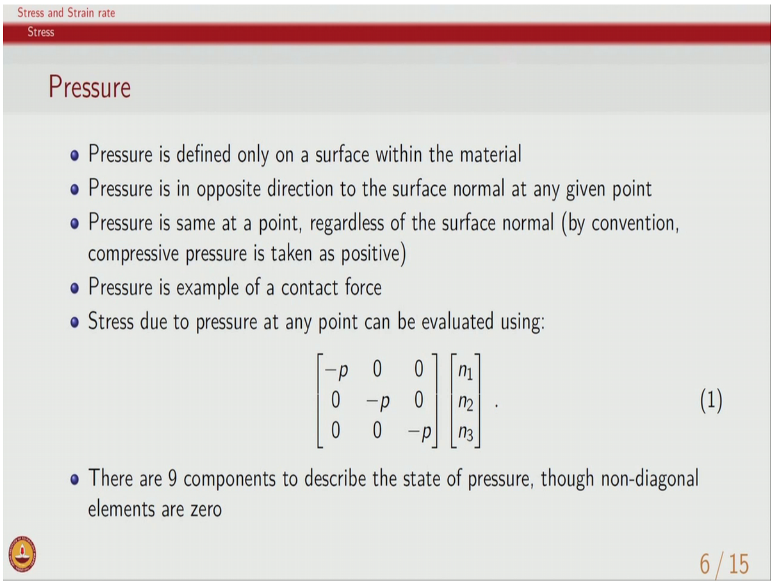

Then we also of course, reviewed what we know from pressure and we showed how for a pressure surface area is essential. And therefore, it is a contact force.

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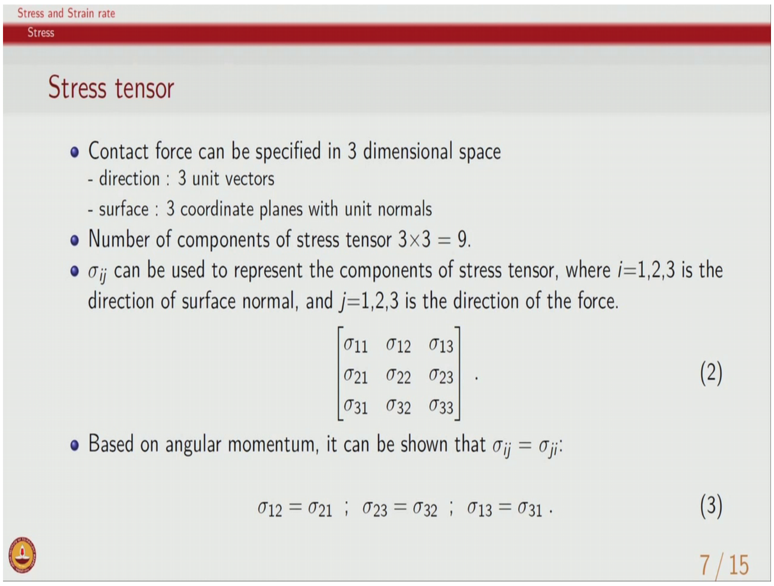

And then in general to specify state of the stress in a material, we have nine components, because there are three directions of force and three surfaces.

And we also said that this is going to be a symmetric tensor for most of the materials that we deal with. In fact, all of the material that we will deal with in this course and so symmetry of stress tensor. Therefore, there are only 6 independent components and of course, depending on which components are 0 and nonzero will then determine; what is the type of flow because in rheology our interest always will be to have one type of flow to begin with, because when we work with a new material it is better to understand that in a simple shear flow or in a uniaxial extensional flow or if it is a constant stress flow and so on.

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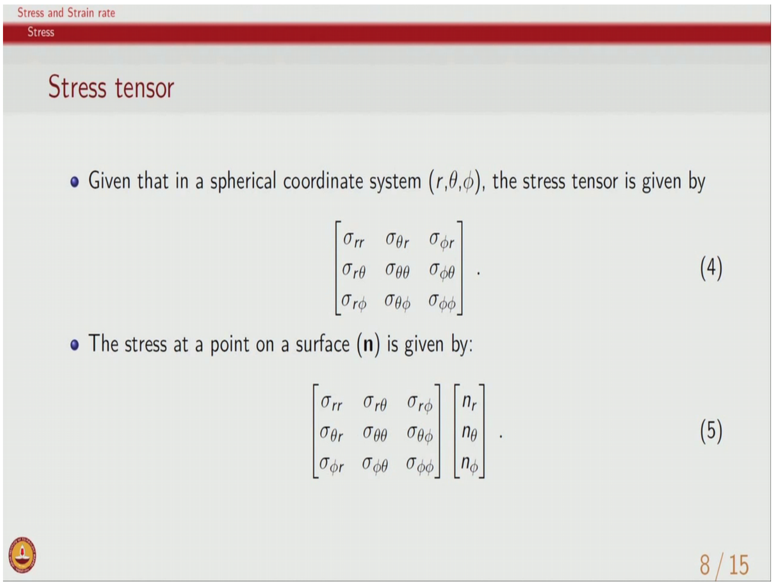

So, therefore, we will need to manipulate stress or measure stress in a controlled way and so we also saw that of course, the components will be different depending on whichever coordinate system we are using. And so with this we also one other important aspect we saw that the overall stress tensor is split into 2.

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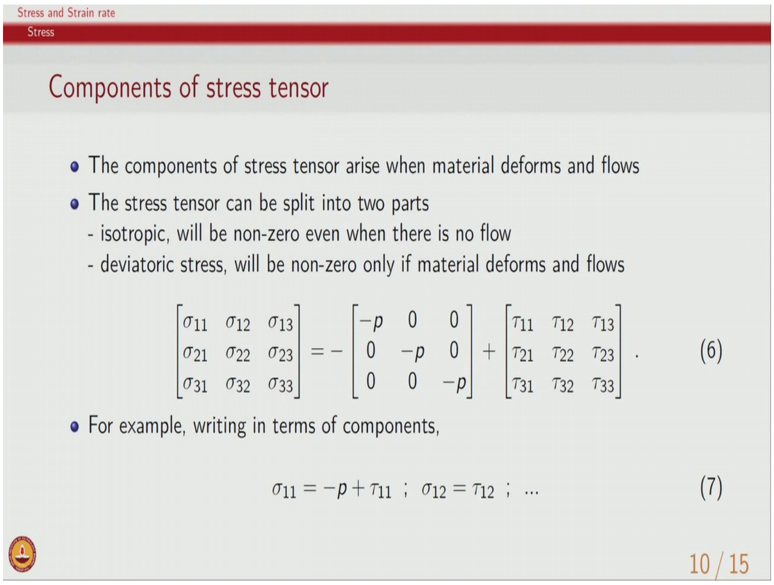

One which is the isotropic which we know as pressure and then the deviatoric stress in fact, it is a deviatoric stress which is most important for these classes because that is those are the stresses in the material which arise due to deformation and flow. So, in the absence of flow and deformation we have only pressure.

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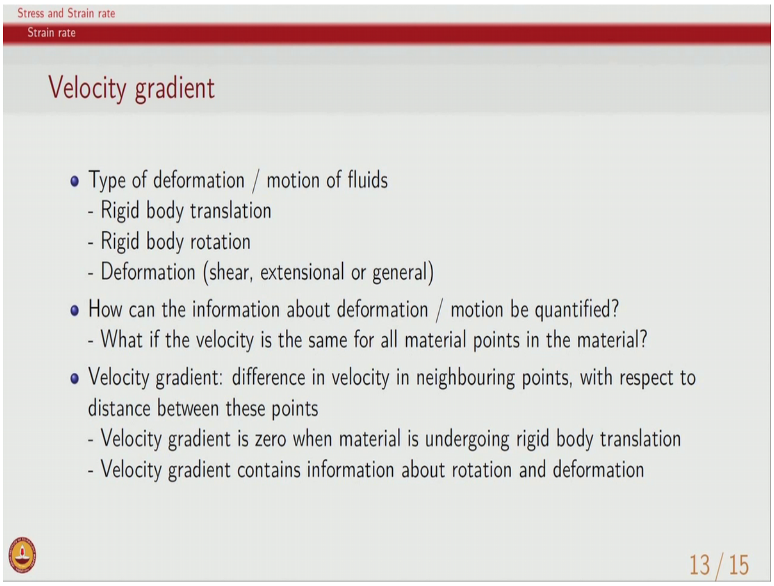

And then finally, what we looked at was velocity gradient. So, what is meant by deformation in a solid what is meant by deformation in a fluid and with this we basically came up with velocity gradient is 0 if the fluid is translating because there is no gradient between 2 points in the material the velocity is uniform for each and every point. So, therefore, its zero, but when there is rigid body rotation or when there is deformation of course, the velocity gradient components will be nonzero.

And so, our interest in this course again will be much more on deformation rigid body rotation will not lead to stress arising in the material we had also said that rotational components of velocity gradients will be important if we are studying let us say a fluid which can be oriented. So, for example, if we are making glass reinforce nylon where there are small glass fibers these glass fibers can orient in flow.

So, then they can rotate glass fiber and so in that case we may be interested in the overall rotational field.

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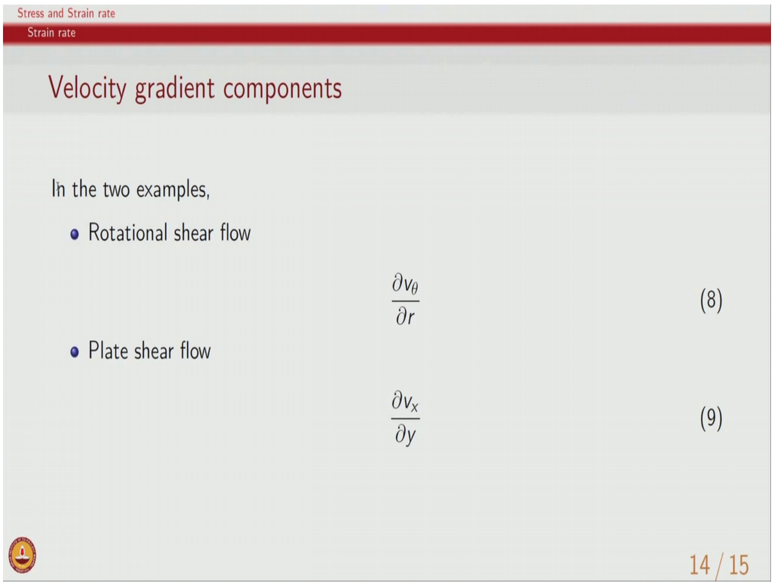

So, with these, we had then summarized that basically what we will have are the components of velocity gradient. And these we will look for let us say 2 different situations.

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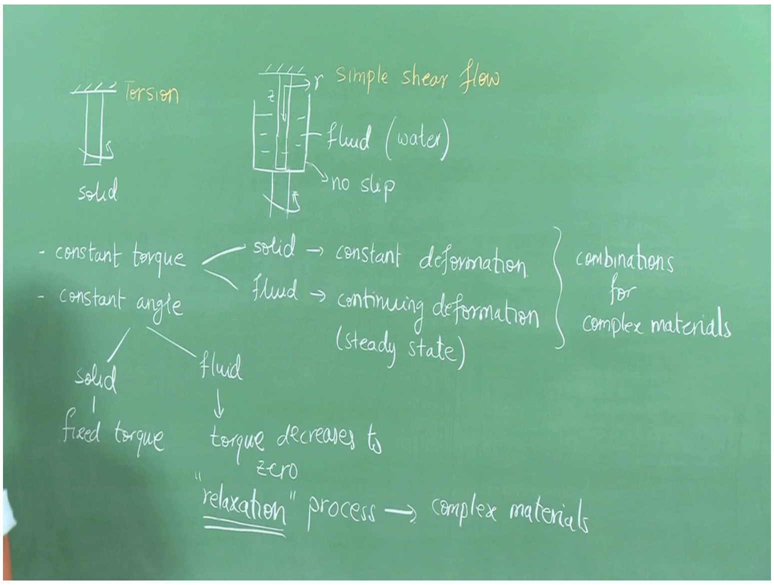

So, we will look at 2 alternate situations one is let us say there is a rod of solid and we twist this.

So, we can do 2 things we can apply a constant torque or we can say that I will twist it by a certain angle. So, we will consider both of those things. So, we can do constant torque or we can say constant angle. So, I can apply a given I will say that 2 by 2 degree I will rotate it no matter what is the force required or torque required and or I will apply certain amount of torque and then I will see how much is the angle by which it rotates.

So, now the same thing I can also think of in terms of a let us say fluid material where of course, what I have to do is take the fluid in a container; so this is the fluid and let us say this fluid is attached to this and I rotate the beaker. So, I take a beaker in which fluid is kept and then I rotate the beaker right. So, this way I am twisting the fluid I will assume that there is no slip at this boundary.

So, that because this is rotating the fluid also which is right next to it will rotate and of course, we know that let us just draw this all the way below. So, that and there is a very small thin gap below. So, the fluid which is right next to this rod which is stationary will not rotate fluid which is next to this outer beaker will rotate. And so, in this case also, again I can think of the same 2, I can apply a constant torque to this and observe what happens or I can apply a constant angle to this and observe what happens.

So, what do you feel will be the difference given that this is a solid material and this is a fluid material. So, let us first look at the constant torque case it will twist by a certain angle and then it will stop there.

Student: Yes.

Right it is and as long as we maintain the torque the angle will remain the same. So, this is fluid of course, which maybe we are thinking an example like water right. So, if I now twist it and apply a constant torque then it will continue to rotate. So, what we notice is for constant torque for solid case for solid, we have constant deformation and for fluid we have continuing deformation right deformation will continue and. In fact, we will reach a steady state right in the sense that as long as torque is there the beaker will continue to rotate at a constant rate so. In fact, we will reach a steady state. So, in this case we have a continuing deformation and. In fact, we will reach a steady state ok.

Now, in the beginning of the course we have thought of that what if these fluid instead of a being like simple fluid like water what if it is a macro molecular solution or a macro molecular melt or what if it is a colloidal dispersion. So, in all of these we are making sure that temperature is constant because temperature changing itself will bring in another variable even for water case if temperature changes clearly in even in for solid when you change the temperature things will change.

So, we are only considering those situations which are isothermal here we saw that there are 2 extreme cases of deformation that in one case you reach a constant deformation case and. In fact, it is a new equilibrium state of the solid material. If you think in terms of crystals of solid what we have done is we have taken the atoms and taken them away from the equilibrium position, but reached a new equilibrium in which case what happens is the strain energy which we have imposed on the material got stored in the material.

Student: Yes.

So, now the new atomic arrangement of the material is such that strain energy plus whatever its internal energy together makes the new configuration possible. And so that is that happens when we have this solid like case and in the fluid like case molecules are all completely randomly going about and then when we start twisting it, it achieves a steady state and fluid keeps on rotating and only thing is there is a velocity gradient setup velocity here is highest velocity here is lowest.

Now, if we have a colloidal system will it initially flow and achieve a constant deformation or will it initially have a constant deformation and then start flowing what are the possibilities. So, what you have to think off is we since we have thought of macromolecule as bead and springs and how they are responding or colloidal systems with some network how they are responding what do you expect these material systems to do what I am trying to point out is. In fact, within the complex materials two types of behavior are possible broadly one which is viscoelastic solid like in which case what we will see is initially there may be some flow, but at long time basically it will achieve a constant deformation or the alternate possibility is that initially there will be some jump in deformation, but at long times it will achieve a steady state.

So, that then we will call it more a fluid like material because its long time response is like fluid. So, so we can have both the possibilities. So, depending on the structure for example, it may be that there is a little bit of flexibility in the colloidal flocks. And therefore, some flow is there, but then the particles get locked and. So, they achieve and then we will say that this material is gel and it does not flow at all it gives a solid like character the reverse possibility is also there that the flocks are there and then they broke break. Therefore, material starts flowing like a fluid.

So, therefore, but initially you may have a jump in deformation because initially the particles respond with a as if they are atoms in an elastic network. Therefore, you will have a sudden deformation and then it will achieve a fluid like state. So, therefore, both of these combinations are possible.

So, combinations of this for complex materials we will have cooling and other things. So, that the temperature of the system is maintained constant. Secondly, in many of the systems, because the shear rates if we are talking about torques which is not very high then the viscous dissipation will be small.

So, that even if there is a temperature change its not very significant to completely alter the properties. So, both of these are possible, if we are doing these experiments rheological experiments at very high strain rates and viscosity is very high than viscous dissipation will be quite high. Then we need to ensure that we have an appropriate temperature control system to assume isothermal there is second case where viscosities are small as well as the small strain rates are also small then in that case the viscous dissipation will be small for us to assume isothermal situation.

So, the this is what you can observe for a complex material now same thing, we can do for constant angle also what if we now say that I apply some amount of torque such that I achieve let us say 2 degree twist. So, in that case what happens to the torque in the solid case it is it will be fixed amount of torque that I have to apply and as long as I keep the twist to be maintained, I will have to continue to keep the torque.

So, therefore, in this case again for solid we have fixed torque that has to be applied what about fluid what happens in case of fluid that again I take this beaker and I rotate it by let us say 10 degrees or 5 degrees.

I take the beaker and I rotate it by 5 degrees and leave it leave the beaker there. So, what I bought what is the torque initially while doing the deformation, I will require some torque, but as soon as I stop the deformation and keep it at the new position torque will immediately fall to 0.

Student: 0.

In schools, we learn like fluid cannot withstand shear that is all this right this property that once we allow some deformation during that period torques will be applied. In fact, why is torque required because we have velocity gradient in the system; fluid while we are applying the rotation. Then therefore, torque is required, but as soon as I finish the deformation now there is no rate of deformation in the fluid and therefore, you can have actually no torque required?

So, what happened to the mechanical energy which was put in the system it is dissipated. So, just the way in this case also when we reach steady state there is a steady dissipation of energy because there is a continuous input of energy also because in this case we are continuing to apply torque. So, there is continuous dissipation in this case what happened is there is a dissipation of energy and therefore, the torque decreases to 0 and in fact, it will instantaneously decrease to 0 by instantaneous we mean is in less than micro seconds and milliseconds and those kind of times the next question is that what happens if we have let us say a macromolecular solution or a complex material there and we are again doing the same thing we are taking it and then twisting it by a small amount and then what do we expect.

In fact, so, that those are 2 experiments. So, one is for example, in this case, we apply a constant torque and then we say we release we let the torque go and then look at what happens to the material. So, that is then an experiment where constant torque and no torque; observation is there. So, what we will observe for the solid cases it may it will recover as soon as we remove the torque; in this case, it will remain wherever it was, it is not going to recover at all.

Student: (Refer Time: 15:01).

Similarly, in this case also when we when I apply the twist I will have to apply torque as soon as I say that I am not going to I will bring the twist back to 0 again the torque will also fall back to 0 in this case if I have to bring it back to 0 again I have to apply torque.

Student: We can opposite torque.

Opposite torque I will have to apply, but as soon as I bring it to 0 again torque will fall to zero. So, therefore, the experiment that you are talking about is applying and then looking at recovery right, but let us right now focus only on the application part; so during the applying part. So, what happens if this is a complex fluid now what would we expect.

Student: Combination of both.

Again it will be combination of both. So, what you would see is this the fact that torque would decrease right so; that means, the material is able to dissipate.

Student: Energy.

Energy.

Student: Energy

At a certain time scale and that time scale will be different depending on what are the internal mechanisms in the material for simple fluids like water and oil the time scales are exceedingly small and we will say dissipation happens instantaneously, but for many of the other like polymer melts or a colloidal system dissipation may happen over seconds or hours and. So, therefore, that requires a significant amount of time for dissipation and what we will say is therefore, there are relaxation processes in the material. So, this is a; this gives us an idea of what is called a relaxation process.

So, by the same token what we can clearly see is in this ideal solid where we say that as long as constant angle is there twist is there and there will be remain fixed torque there are no relaxation processes there is never any dissipation of energy for a simple fluids there is always instantaneous relaxation, but for complex fluids, there will be relaxation processes that we can characterize.

So, this is a this is a word which you will start hearing more and more what we will see is like the mechanisms that I talked about in case of colloidal system we said that there is interaction between particles that will have one type of timescale and one type of relaxation process we also said between one single particle and surrounding fluid drag force. So, that is another mechanism another type of relaxation process then we may also have hydrodynamic interaction.

So, each of these different mechanisms at the microscopic scale actually will bring in different types of relaxation processes and therefore, the complex fluid response or complex material response will be a combination of all these relaxation processes that are happening in the material and that is why it is important for us to try to do rheology on such materials to try to understand and. In fact, our hope will be that by looking at such experiments by doing such experiments we can then figure out what are the relaxation phenomena that are involved in the material.

So, then it can help us in designing better materials or understanding the behavior of materials or process the materials better and so on. So, this is response to the; of the material to this simplified in this case this is actually what we are doing is shear in this case way we call it torsion right. So, what we are doing here is a simple shear flow and what we did here was torsion of a solid rod.

So, given that more often than not in our course we will be dealing with fluid like materials what we can say is in this case if we look at a coordinate system and we say that basically you have r r and then z right cylindrical coordinate system. So, what we have is velocity only in theta direction.

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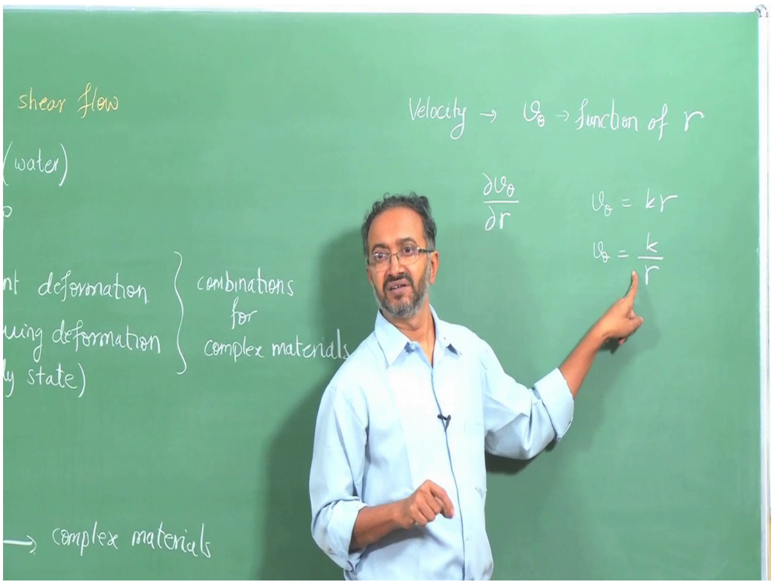

So, therefore, what we have is velocity only in theta direction and also this is only a function of r right if in the z direction, there is no difference in velocity because the whole beaker is rotating we assume for example, that the rotation rate are small enough that we do not have any of the features which are associated with very high inertial forces that is an important assumption that many of our rheological analysis; we will do. We will always assume that viscous forces dominate inertial forces are negligible.

Student: (Refer Time: 20:32).

In other words Reynolds number is small because this will help us in understanding the contact stresses and the deviatoric stresses that arise in the material because that is our main goal to try to find out what are the mechanisms by which contact forces and deviatoric stress is generated in the fluid and. So, the only component of therefore, velocity gradient which is nonzero is del v theta by del r.

Now is there rotation in this fluid when this is happening they is there deformation is there translation right these are the three things right. So, is fluid translating is the is there rigid body translation of the fluid is there rigid body rotation of the fluid is there deformation in the fluid is there a rigid body translation.

Student: No.

No right there at each and every point in the fluid there is velocity is different. So, it is not like I take a fluid in a beaker and then slowly if I move like that then it is a rigid body translation because each and every point will move the same, but here there is no translation what about rotation; rotation is there.

Student: Same.

If fluid is rotating, but do not confuse this with the rotation that we discussed which is local rotation.

Student: Yes.

What you can do is you can go back and look at preliminary fluid mechanics books and you can look at these 2 flows right there are 2 types of again both of these are tangential flows velocity is only in the theta direction, but you can see you can work with these 2 examples and you can see that this is a rigid body rotation while this is an irrotational flow, right. So, for which there is no rotation; local rotation.

Student: Yes.

So, just because fluid has a;

Student: (Refer Time: 22:38) vortex.

Theta direction and azimuthal yes free vortex is these 2 are in fact, the combination of these 2 is a good model for a vortex. So, therefore, just because we have v theta here should not automatically mean that there is rotation, but if you, but since this del v theta by del r is nonzero and we have defined the spin tensor or vorticity tensor earlier.

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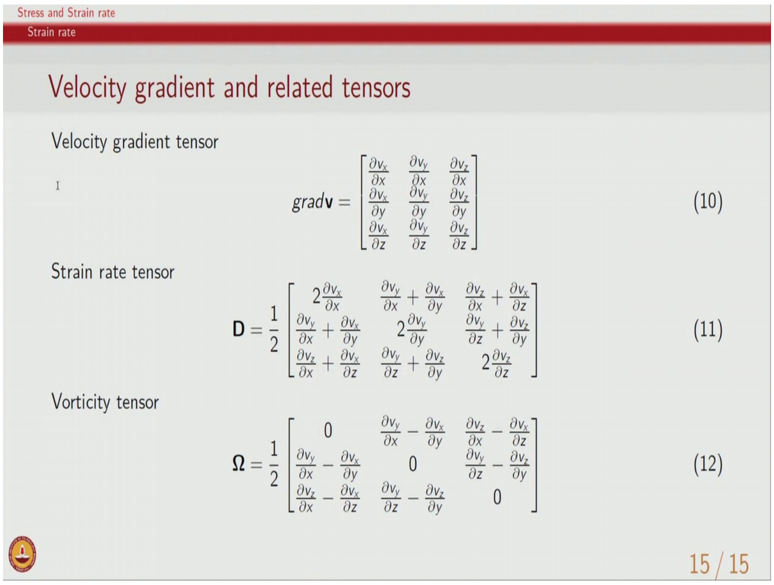

You will notice that it will be nonzero and that we can just see on the next slide. So, we can see that the non-dagger whenever you have one of the shear components nonzero, we will have in fact;

Student: (Refer Time: 23:19)

The omega to be nonzero.

And D is of course, our strain rate tensor. So, we will have del v x by del y or in this case del v theta by del del r as the nonzero component and of course, the gradient of v tensor as we saw earlier contains information about both rotation.

Student: (Refer Time: 23:38).

Deformation; so that is why we split the velocity gradient tensor into the strain rate tensor which contains information only about deformation and then the vorticity tensor which contains information only about rigid body rotation.

With this, then we now have finished the discussion which is related to the stress as well as strain rate tensors and what is meant by the deformation and rate of deformation in general complex materials.