Rheology of Complex Materials
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Lecture – 36
Rotational rheometry: Material functions

So, these set of lectures which are related to rotational rheometry, we will look at the how closely we can match the experimental conditions that we used as rheologist to what are the theoretical assumptions which are used in analysing the phenomenon. For example, we have seen that there will be shear flow that we will say we are going to conduct. Now, how closely is the flow shear flow only, so that there are no extensional components, so that has to be ensured when we do shear flow experiments, because all our analysis will be based on the assumption that there are no extensional components during the flow.

So, how closely are we mimicking that situation in an experimentals condition. So, closely we need to be always aware of what are all the assumptions that I have gone on to one particular type of measurement. And ensure through experimental protocols that we are as close to those assumptions as possible. And more importantly, if we do let us say rheometry experiments and we get the data, can we by going through the data recognise if there is something which is experimental artefact. So, artefact arises because the assumptions that we made are being violated.

One simple thing could be let us say no slip at the wall of the rheometre geometries. Most of our analysis we will assume no slip, but if material start slipping to some degree because quite often the material may not slip perfectly. So, then there will be certain then we will say that oh my data, so we can start interpreting let say whatever material function we measure and start interpreting various things and we will say it is related to structure, but actually it is related to the slip . So, therefore, we need to make sure that we are aware of all the assumptions that are involved in calculation of material function. And more importantly, if we get the data we should be able to analyze so that we should be able to figure out if there is an artefact which is there in the data.

Effectively we will need to again look at how material functions are defined. So, we will go through one example of cone and plate viscometer and the measurement of viscosity.

So, that fluid mechanically we will see what are all the assumptions and then we will come back and then see that when I do experiment when I load fluid into the cone and plate geometry, what are all possible ways in which I can violate those assumptions and what kind of artefacts will that lead to. So, this is the overall scheme for the next few lectures in which we will discuss rotational rheometry. So, first in this segment, we will go through the summary of all the material functions that we have defined so far in the course.

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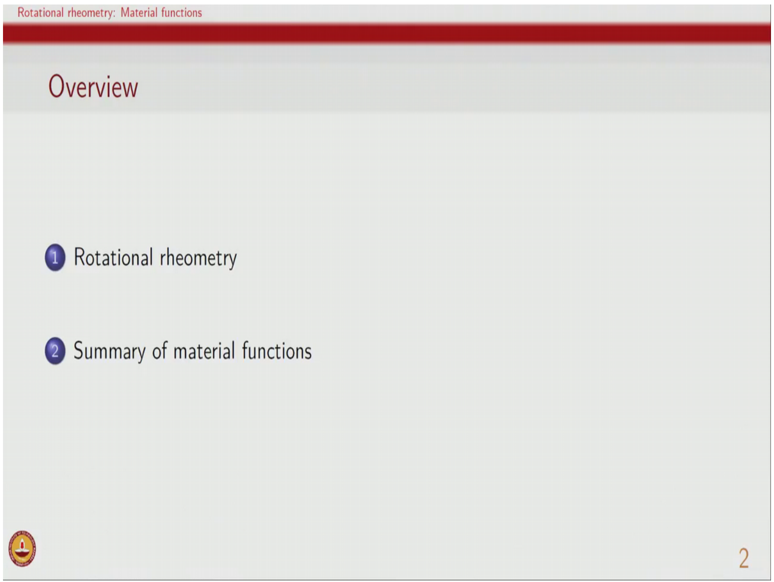

So, we will look at rotational rheometry generally and then look at summary of material functions. And then in the next segments we will look at cone and plate geometry and its fluid mechanical solution.

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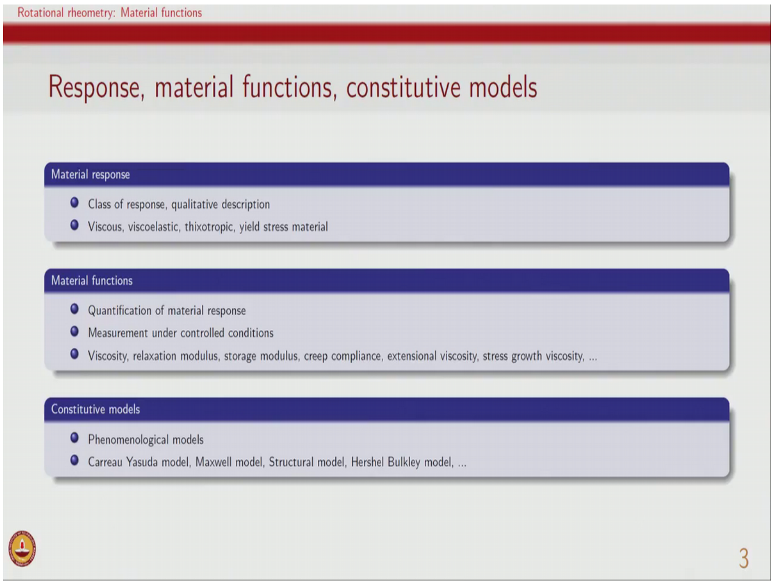

So, we been following this overall approach in looking at the rheological response we have said that we will look at qualitatively the response through these different types of response. So, we try to characterize whether it is a viscoelastic response, whether thixotropic or yield stress material. So, depending on this then we can then investigate and find out which material functions are useful. So, to do quantification we use the material functions. And then of course, we are also parallely always looking at some constitutive model which helps us explain. So, for stress relaxation, we saw Maxwell model for creep we saw, standard linear solid model for normal; stress differences we saw upper convicted Maxwell model. So, there was always one simple model which was useful for us to show the material function that we were trying to understand.

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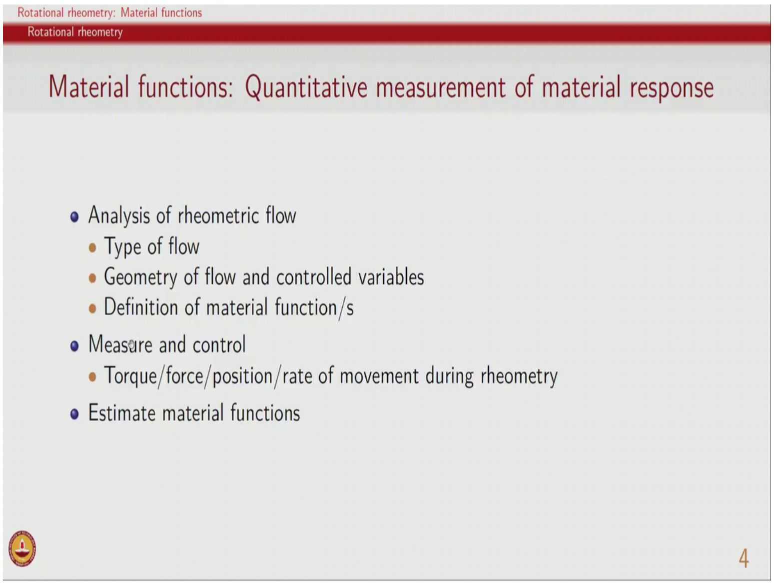

So, we will continue and. So, basically the material functions which are quantitative measurement of material response are based on analysis of a rheometric flow. So, this rheometric flow could be based on the type of flow that we have decided to impose on the material. Given a type of flow there are still possibilities of several geometries. So, just because we decide a type it need not freezes into one particular geometry. For example, shear can be imposed we have seen already in cone and plate, it could be parallel plate. So, there are several possibilities as far as imposing shear is concerned.

Similarly, even if we do extensional flow, we can do it in the form of uniaxial or biaxial, it can be a cylindrical rod. So, there are various possibilities of doing the various geometries that can be chosen to impose a particular type of flow. And then of course, based on these two we finally define very precisely what a material function is. And of course, from an experimental or analysis point of view, we are controlling some variable and measuring some other variable. So, we saw that in a stress relaxation experiment, we will control strain. And strain will be can be controlled using position. And of course, what we will be measuring is either a force or a torque.

If we are doing a creep experiment, then maybe torque and force is being controlled and position or rate of movement will be measured. So, either of these variables will either be a measured variable and the others will be controlled variables. So, depending on what is the nature of rheometric flow that we have decided, we will choose one of these set of measurement variables and control variables. And this is something very important in terms of understanding the rheometer response also. So, there are some rheometers which naturally are better in terms of controlling the position or the strain; while some there are some other rheometers which are far better in terms of controlling the force depending on the make of the rheometer and what is the overall sensing elements as well as the operating elements in it.

So, therefore, you will hear of strain control rheometers or stress controlled rheometers. So, therefore, it is a better for us to know what is the control variable and what is the measured variable. So, if on a stress controled rheometer, if you control strain, it can be done, but we must always be aware that maybe the sense the basic rheometer is made in a way that it control stress strain control can happen only if feedback is done. So, what the instrument will try to do is applies little bit of stress, then measures strain. And let say we have asked it to do 5 percent strain, so it will apply some stress see what is the strain and it will realise oh it is not 5, then it will go back and change that stress. So, therefore, there is a feedback loop through which it will control.

So, therefore, this measurement and control variables are also important for us to note when we are looking at rheological analysis. And of course, based on if we have done our analysis of rheometric flow correctly decided the type properly, make sure the geometry is well defined, and therefore, definition of material functions is quite clear. And if we are able to measure and control variables appropriately, then we can estimate the material function quantitatively. And hopefully in this estimate therefore, there may not be many artefacts.

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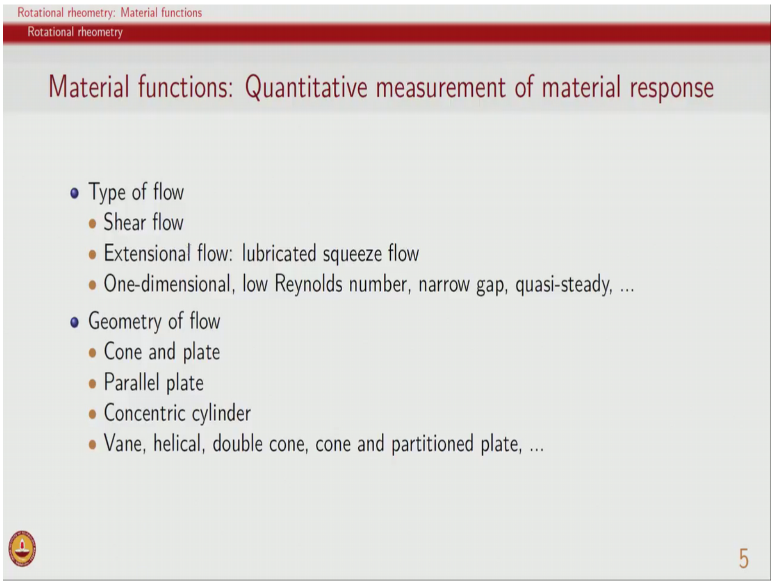

So, now let us look at each of these three. The type of flow for example can be shear flow; it can be extensional flow. Extensional flow as we saw can be done in lubricated squeeze flow also which we have discussed earlier. We can take the material between two plates and squeeze and have the plates lubricated, so that materials slips. So, this is another example where an artefact can arise. So, if let us say we ensure slip by applying either a waxy coating or maybe a teflon plates, so that hydrophilic materials will slip, but the slip may not be perfect there may be a little bit of no slip or little bit of sticking.

So, therefore, we will have to do many times more systematic experiments. We may have to change the rate of squeezing, we may have to apply our slipping coating two-three different way, or maybe use two-three different surfaces and then analyze and make sure that the assumption of perfect slip is being obeyed. In all of this of course, as rheologist, we all always also test with standard fluids. There are always standard fluids available and for which we know completely the about the response is. So, generally we also tend to put the standard fluids in the rheometer and then analyze the response and make sure that we are getting the response that is expected.

And once we decide the type of flow, there are various other assumptions that go into the analysis. For example, we may assume that flow is only one-dimensional; we will more often than not assume that it is very low Reynolds number quite often we are looking at very thin gaps in the rheometer. So, if the diameter of the cylinder is 50 mm, the gap between the in the annular region maybe only 1 mm. So, therefore, it is a very thin gap cone and plate the separation between cone and plate is in microns 50 microns or 100 micrometres. So, therefore, it is a very thin gap and that is the characteristic dimension in defining Reynolds number.

So, therefore, Reynolds number is quite often low. Reynolds number is also low because quite often these complex materials have high nominal viscosity. Their viscosity is generally definitely an order of magnitude or even more higher than water. So, generally viscosity is high, the dimensions are low, so Reynolds number ends up being very small, but in all analysis this is very crucial. So, quite often in rheometer operation you will hear that inertial effects are important. So, we may do for example, an oscillatory shear and we may get g prime as a function of frequency and then looking at the data especially at high frequency somebody may open that oh looks like your high frequency data is suspect there may be inertial effects.

And so inertial effects will be important wherever Reynolds number is significant. So, we need to ensure that the Reynolds number is sufficiently low, and therefore, the fluid inertia or the material inertia is not playing a big role or not playing a substantial role or significant role, so that you can ignore it and therefore, measure properties the way we are meaning to do. So, low Reynolds number, narrow gap are analysis assumptions which are always done. Similarly, there is can be an assumption of quasi-steady. So, the squeeze flow that I mentioned it is actually depending on how the analysis is done. If you do let us say squeeze flow, which is not lubricated then the material does not really slip.

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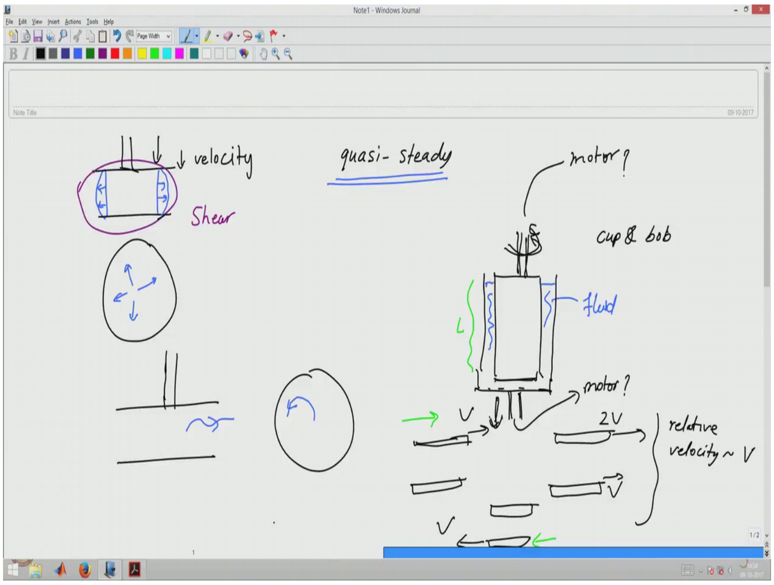

So, for example, this also we have seen as one of the examples that if you have a parallel plate and the plate is moving down, and then if you have let us say fluid here, then the fluid will start moving radially outwards. So, if you look at it from top, basically you since see your pushing the fluid below, the fluid will be moving in all radial direction. And in this case, you can actually the plate is being pushed continuously. So, therefore, there is a velocity of the plate. So, this plate is being pushed down with a velocity.

Now, how to analyse this problem? So, we quite often use an assumption called quasi-steady. So, we will say that at one instant of time, if this velocity is specified, let me try to find what is the velocity profile, because remember the shear is happening in this region, shear is happening here. And in the end, this is a velocity profile that we are we are interested in finding out. So, what we say is we will assume as if the plate is coming step by step instead of continuously. And we can attempt solution at each and every stage.

And of course, we know that overall things are dependent on time because plate is continuously moving, and therefore, velocity witted here will also be continuously changing, but we seek a solution by saying we will assume quasi-steady operation. So, as if in one instant of time material flow at least within the geometry the radial flow is going to be steady flow, and yeah.

Student: (Refer Time: 14:11)

Then depending on the rate of motion of the plate, the assumptions that we apply here may or may not be valid right if plate is moving too fast.

Student: because many quasi studies we used for isothermal (Refer Time: 14:29)

Right yeah. So, quasi isothermal or yeah, so anytime there is a or for example, in thermodynamics we sometime use the quasi equilibrium. So, we say that when system is evolving from one state to another, we realize that it will go away from equilibrium, but instead we assume that it is going through steps which are very incremental and in each case that it never goes too far away from equilibrium. So, here also it is similar assumption.

So, even if the let say the rate is very fast as long as the fluid flow is only in radial direction, then we are ok again. So, it depends on what is the behaviour of the system. It need not mean that in case of equilibrium quasi equilibrium assumption also, the rate is not determining factor in determining how far away from equilibrium you have gone. Similarly, in this case also whether the plate is moving too fast or slow will not necessarily determine whether we can make quasi-steady assumption or not; it is more dependent on how the velocity profile looks like.

For example, if it is at some rate rather than going like this, if let us say the fluid velocity profile ends up being for some reason because of the rate at which it is moving if a fluid is moving something like this. Write that it starts acquiring z motion which is much more significant or because of the way the plate is being pushed there is instability and when you look it from top, the fluid in addition to moving in r-direction, it is also moving in theta direction. So, these are the assumptions which are completely going to break down. So, then that case there is no point mentioning quasi-steady, because everything depends on time, and the detail pro profiles is very different compared to what we are trying to analyze.

So, therefore, there is a whole lot of assumption regarding type of flow that go into analysing and making sure that we have a rheometric flow. The other important choices of course, given type of flow can be done in several types of geometries. So, throughout the course we have discussed cone and plate and parallel plate quite significantly, there are also concentric cylinders. So, which is where we choose two cylinders and then one of them is rotating, so it is also called cup and bob. So, we have an annular region in which fluid is placed. So, this is where a fluid is placed and then the geometry is rotated. So, in this case, do you have any idea about whether if let us say we have the option of rotating the cup and rotating the bob which is better for us to rotate.

Student: The bob more.

Yeah, why is that, why is it? In the sense one can do rotation of the see in the end it is only relative velocity between these two moving surfaces. So, for example, even if you have let us say the parallel plate example that we been discussing in class quite often if this is moving with velocity v, the same thing can be achieved by saying that this is moving with velocity v and this is moving with velocity v right. This is the same identical flow because rest of it is rigid body translation right. Same thing could also be done by saying that this plate is stationary while this plate is moving to the left with v. So, all of these are identical situation in which basically relative velocity between the two plates is v.

So, from a fluid mechanical point of view all of these are identical situations. So, similarly in this cup and bob also, we can have the cup rotating or the bob rotating. So, which one would be better and why is a good question to ask. So, any idea about it?

Student: Rotating a how you will come to normally in these cases that the rotation will be.

No. So, you can for example, this can be also mounted on a shaft, and this is also mounted on a shaft right. So, of course, one thing is you can have motor here, this will be connected to motor right, alternately this can also be connected to motor.

Student: (Refer Time: 19:23) height also that liquid height.

Student: how much you have been in case of all through (Refer Time: 19:28).

If both cases we can I mean so this is the level to which you will usually, so there will in such cup and bob geometry, there will always be a level indicator to say that you should fill up to that level because the assumption again will be that sharing is happening throughout the geometry.

Student: (Refer Time: 19:48).

Ah.

Student: (Refer Time: 19:51).

What do you mean by fluid surface is too much?

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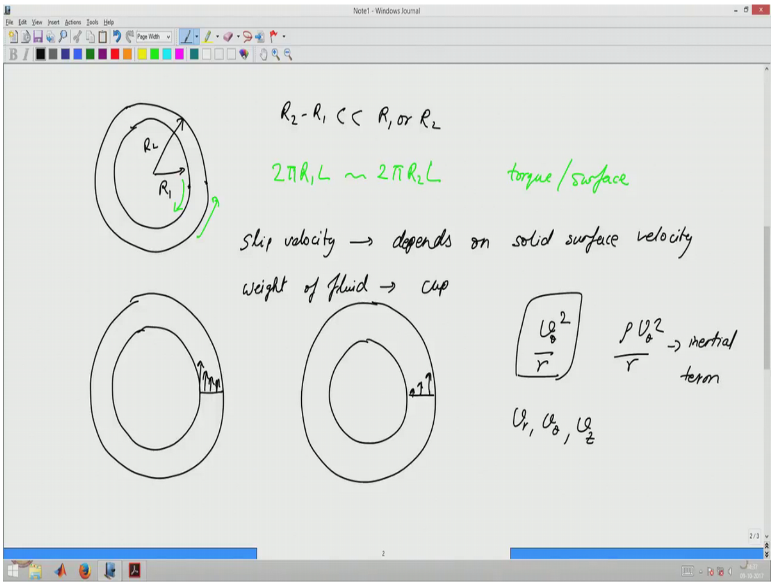

See because you remember that this is what we have always said is let us say this is R 1 and this is R 2 then generally the R 2 minus R 1 will be much less than R 1 or R 2 right.

Student: Yes.

Because it is a thin gap, we would like to have.

Student: It will take the load of the liquid also.

So, but.

Student: (Refer Time: 20:31).

Yeah.

Student: (Refer Time: 20:35).

So, will the stress, so are you saying the stress will be more here as supposed to here?

Student: No in the outer surface (Refer Time: 20:45).

Yeah.

Student: (Refer Time: 20:48).

But what will be the incremental difference in the torques. So, maybe the torque first of all you we will have to ensure that is the torque different. So, for example, in the earlier case that I showed in this case whether we are moving them in the this top plate in the positive direction or the bottom plate in the negative direction the torque requirements will be entirely identical.

Student: Yes sir.

Right in this case there is no difference. So, that is the question we are also asking that in this case also if we have the one option is that the inner rotates in one direction or the same rate the outer one rotates and, but one possibilities because there is a difference right the perimeter in the two cases are different. And that is why you are saying in one case it will be 2 pi R 1 in the other case it will be 2 pi R 2 and of course, the L.

Student: Yes sir.

L is the length. So, this L is the length. So, therefore, 2 pi R 1 L and 2 pi R 2 L will be the two surfaces. So, possibly is there maybe differences of torque, what other factor would there be?

Student: (Refer Time: 22:03) surface area is smaller of that, so that.

So, that that we already said. So, torque related, surface area related, so all of these are related to one set of factors

Student: Resistance.

So, resistance, torque, surface area, all of them are related to the fact that more surface area is there on the outer plate. What other factor could be there in terms of defining the.

Student: slipping (Refer Time: 22:33).

So, we will slipping the affected based on whether we rotate the outer geometry or whether inner geometry.

Student: the outer rotating the velocity profile (Refer Time: 22:43).

Yes.

Student: So, then they should be equal to friction between the between the bob and so that the fluid does not slip (Refer Time: 22:50).

But, so your, so then we should we should qualify that statement by saying that it is possible that the slip characteristics may depend on velocity. And it is likely that if velocity is are higher slip may happen right. In that case, but then inner plate will also have the slip because we are going to rotate both them.

Student: Velocity may (Refer Time: 23:17).

So, if at all there is, so quite often you may have a case where slip velocity let us say depends on slip velocity depends on a solid surface velocity right, but then both inner and outer surfaces are going to be identical. So, either we will have slip at the inner surface, if we do rotate outer we will have slip at the outer surface. So, therefore, that difference may not translate much. Is there any other factor?

Student: (Refer Time: 23:58) outer cup it will take the load of the liquid also.

Ah

Student: (Refer Time: 24:00).

But that is in the vertical direction right. So, if at yeah, so and the other thing is given that it is a thin gap, the amount of fluid is going to be small.

Student: (Refer Time: 24:11).

Right so, but yeah it is true that in this direction they will be gravitational load which the shaft will have to with stand, so that will be there, but we expect that load to be not very significant. So, weight of the fluid is there and that will be there on the cup right the cup will have to with stand.

Student: (Refer Time: 24:37) spindle also bob also having the weightage.

Ah

Student: (Refer Time: 24:39) more than that, but that.

Exactly.

Student: (Refer Time: 24:42) fluid whatever we are taking.

Ah.

Student: The density may not same for all.

But yeah. So, the what, but only thing is the torque is being measured in this direction and weight is in the other direction.

Student: 90 degree

So, therefore, the weight even if it is different and even if we do not know the density of the fluid very well, it is not going to contribute in the torque direction.

Student: Yes.

One other factor that you could have is what if your motor efficiency is different for different weight.

Student: Yes.

So, that, but generally we will choose a motor for rheometer which at least for a good range of a weights will work well.

Student: Yes sir.

So, that we are able to transmit the load that we want or we are able to rotate it at the rate we want.

Student: Yes sir.

For a given set of weights. So, it is hopefully not that sensitive to that contribution; though it can be one factor. What else could be? So, if maybe just you the look at what direction is the flow in.

Student: (Refer Time: 25:45) theta direction.

Theta direction right, the flow is only in theta direction. So, if we the inner case is rotating, then the velocity will be something like this right. And it will go down to zero at the outer surface.

Student: Outer surface.

And if we have the other way where the outer surface is rotating then it will be like this right.

Student: (Refer Time: 26:13 sir if the outer is rotating radial directions (Refer Time: 26:16) radial flow because.

Ah

Student: (Refer Time: 26:17).

Yeah. So, is that so in fact, that is the reason I wanted you to think of from the beginning right that is why I have been asking more and more as to so now, as soon as I draw this it becomes clear.

Student: Yes sir.

That in one case we see the theta direction motion is perfectly fine that is what we want. We do not want fluid to be moving in radial direction, but we always know that whenever there is a v theta motion, there is always v theta square by r is the centrifugal centripetal forces in the radial direction.

Student: So, (Refer Time: 26:52).

So, it will start having flow in fact in r directions.

Student: (Refer Time: 26:58).

Yeah it will it will start getting basically v r, v theta and in fact v z also.

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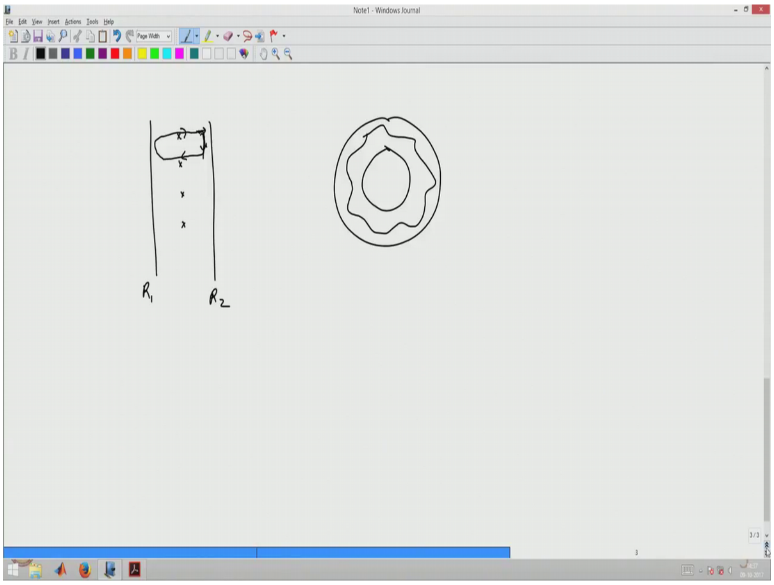

What will happen is if I draw let us say the annular gap again, so let us say this is the annular gap this is the inner cylinder, so this is R 1 and this is R 2. And ideally we are hoping that fluid is moving only in theta direction. So, let us say it is going inside the, so therefore, I am drawing it like this I hope you are all familiar that this means that fluid is moving in theta direction. But let us say because of this motion and r this fluid element starts moving in r direction, then what will happen is since it will encounter the wall it will have to also come back and it may we may get a roll like that.

So, if you look at it from top, what will happen is a fluid element which is let us say in this annular region will be moving like this right, it is moving in the radial direction also. And in theta direction of course, we will be moving because we are rotating one of the similarly when I look in z it is also moving in z direction. So, the basic analysis point that we had that look we are only imposing theta motion, and velocity has to be only in theta direction will be very severely violated if we have this kind of a breakage. So, from that point of you at least looks like that to minimise the inertial forces in fact this is an example of inertial force. So, rho v theta squared by r will be the inertial term. So, it is better for us to have v theta high for lower r.