Introduction to Soft Matter
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Lecture 20
Viscoelastic effects

So hello and welcome back to another lecture on Introduction to Soft Matter. And in the last class we were discussing the simple shear flows, and we are going to continue the discussion. And there is a particular reason why we are continuing this discussion. That is because we want to understand a couple of very important terms that are related to non-Newtonian flows and polymeric fluid flows.

So last time, we were discussing this idea of the simple shear flows if you recall.

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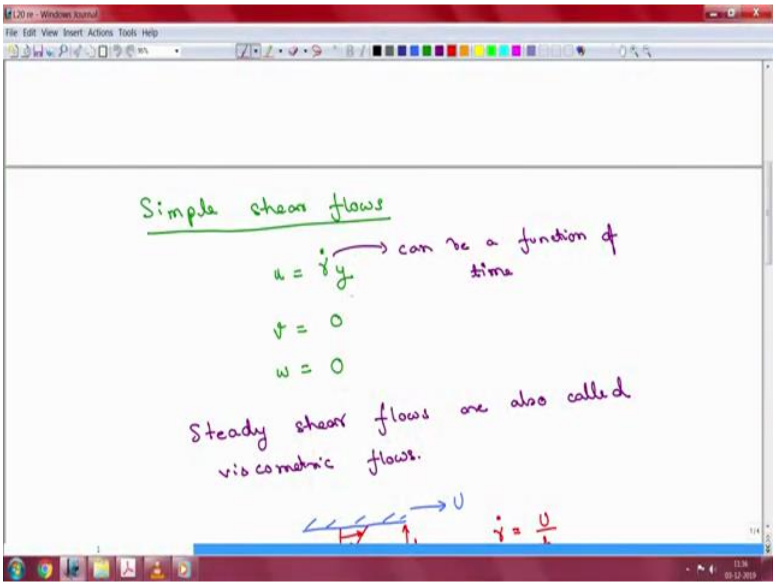

And here we had said that the function u is function of y and is given by the flow field is given by these velocity fields where we have written it down in the competent forms so we have U, V and W as the velocity components.

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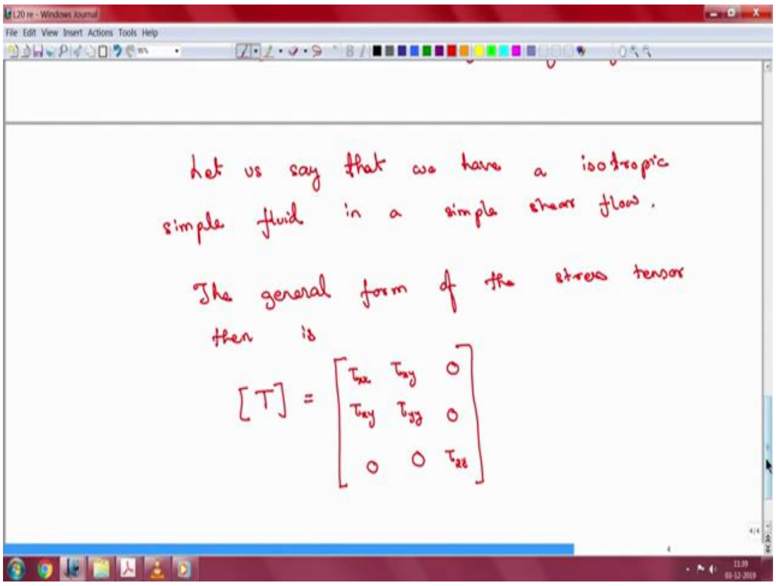

So now, let us say that we have a isotropic simple fluid in a simple shear flow. We know the form of the velocity field but the question is what is going to be the form of the stress tensor? So we want to now understand how the stresses in the fluid are going to develop. Now the general form, so to say the general form of the stress tensor then is, so let us say we have a stress tensor, I am just going to write it in matrix form.

So I just put this bracket which means that I am going to write it in matrix form. So obviously, the flow is three dimensional. So your stress tensor is going to have 3 into 3 components. The question is what are these different components? So in the simple shear flow, as we saw that the flow velocity is basically, the third dimension is not that important. So you are not having any flow in that direction.

So the flow is essentially in a sense it is a two dimensional flow. Now, here what you will have is in a general case you will have, so in the Newtonian case you will have a shear stress. These are going to be symmetric because we have already discussed that. That the stress tensor for fluid element is going to be symmetric due to the application of the principle of linear angular momentum. So these are going to be there and the question is what is going to be in these two positions.

Now, if this is just a Newtonian fluid, you will only have the pressure terms contributing to the normal stresses here and they would be equal in that case. But here, in the more general case, you can have pressure, you can have force stresses that are going to develop in these directions. And since this is a basically a two dimensional flow, your other terms are basically 0.

You cannot put a 0 here by the way, because even though the fluid is, flow is two dimensional, you still have a pressure term that will contribute to a normal stress. So this is the most generic form of the stress tensor for a simple shear case.

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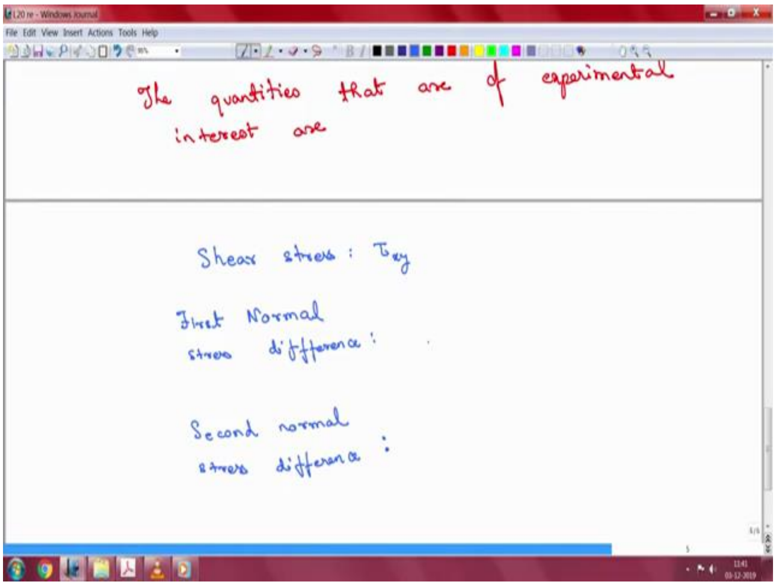

Now, the quantities that are of interest here, that are of experimental interest here that are of experimental interest are, and here say, so one of the quantities is obviously the shear stress. You have already written that down, Tao xy. And then you have two other important terms which are called the first normal stress difference. And similarly, you have another term which is going to be called the second normal stress difference. I will define mathematically these terms in a second here.

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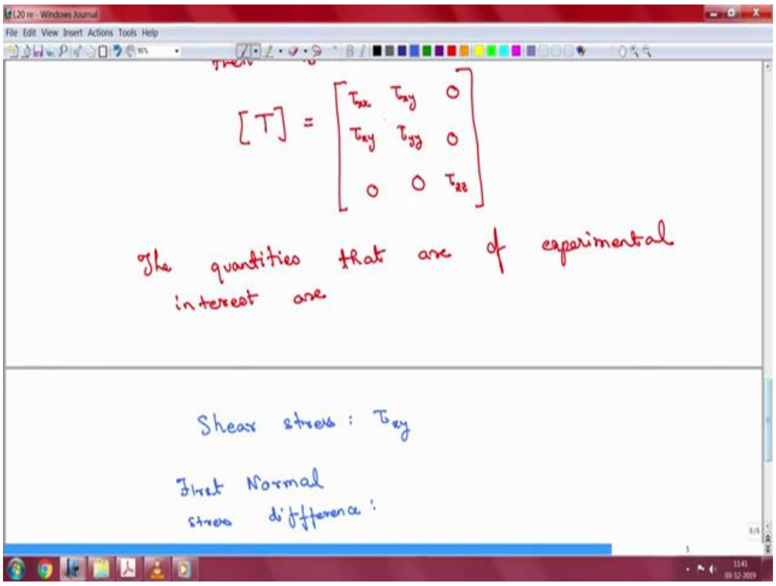

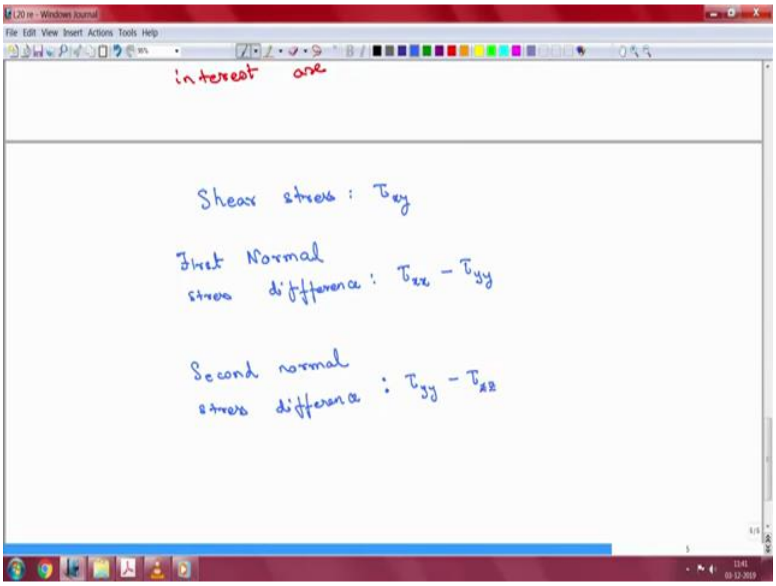

So the first normal stress difference is the difference of these two components right here. So Tao xx minus Tao yy, so let us write that down. So this is Tao xx minus Tao yy. Similarly, the second normal stress difference by a similar logic would be Tao yy minus Tao zz.

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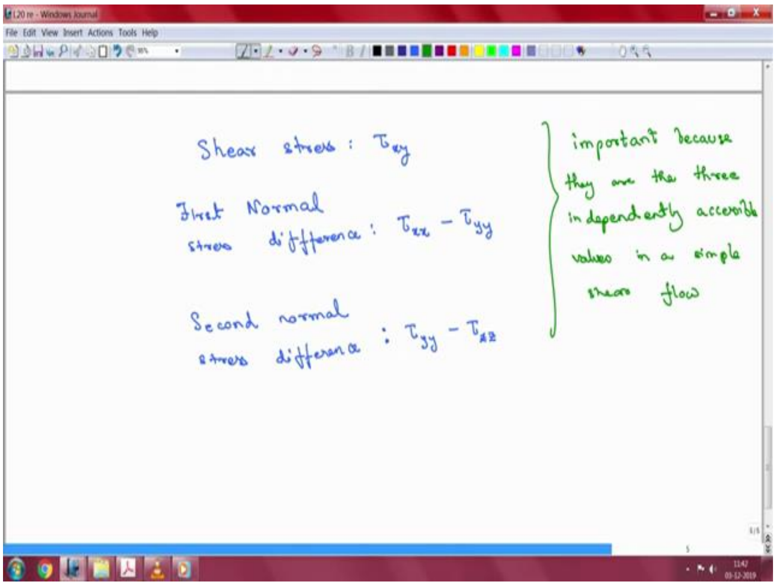

Now, they are important because they are the three independently accessible values in a simple shear flow, so important because they are the three independently accessible values in a simple shear flow, experimentally accessible.

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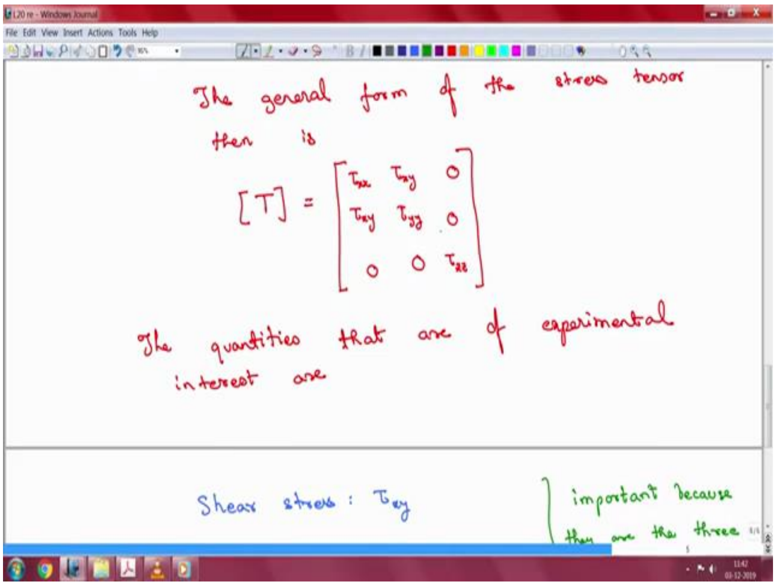

Now, going back to this, as I had said before that if it is a Newtonian fluid, then Tao xx minus these normal terms Tao xx, Tao yy and Tao zz are only the pressure terms. So they are actually the same. And for a Newtonian fluid, your first normal stress difference and the second normal stress difference is 0, but that cannot be said so for a more generic case.

So in a more general case you can have a finite first normal stress difference and a finite second normal stress difference. And this you have this shear stress, obviously in all cases.

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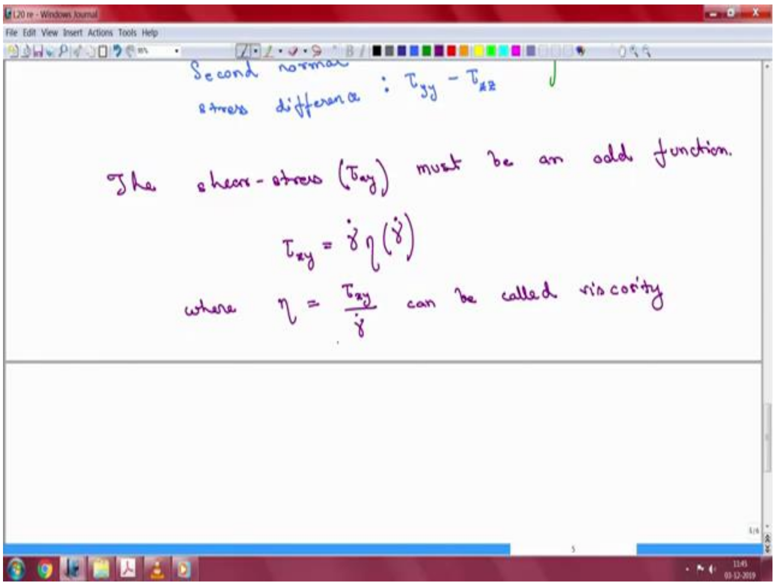

Now, this shear stress here, so this shear stress must be an odd function. I mean you can look at the, you can probably figure that out from the physical argument that is the direction of flow changes, then Tao xy sign should change. Its value is the flow remains exactly the same, but the direction of u is reversed, then Tao xy will have the same value but with a different sign.

So this will be an odd function. So maybe we can write this Tao xy as some gamma dot, this gamma dot is the generalized, is the shear rate and you have some eta which is a function of gamma dot where this eta is how we define, so when we write gamma dot in the bracket, it means that eta is a functional gamma dot. S eta is basically a function which is given by this and this and this can be called viscosity.

And now this is an even function because Tao xy is a odd function and you have gamma dot, so if both the signs reverse then but the sign of eta will remain the same. So this is an even function.

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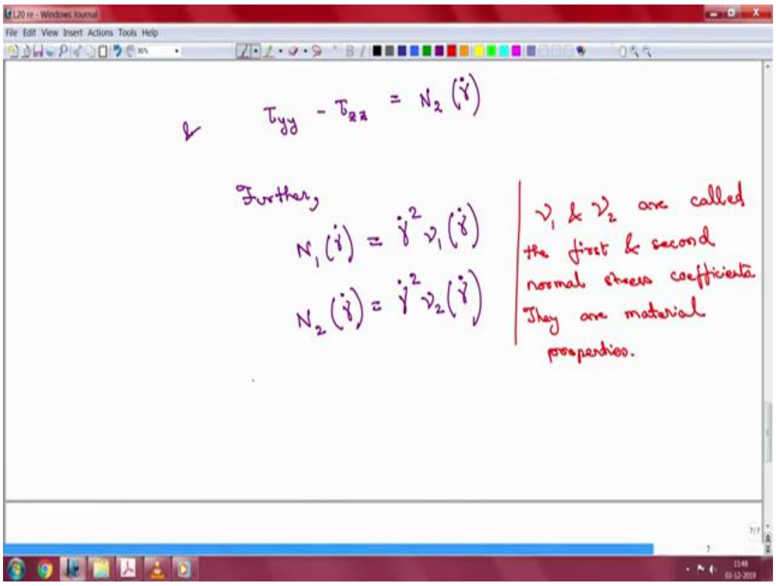

We can also argue and show that the first normal stress difference Tao xx minus Tao yy and, and I am just going to complete this in a second and the other one which is the second normal stress difference, they are actually even functions. And you can write this as some N1, which is an unknown function and it is dependent on gamma dot.

So the first normal stress difference is equal to N1, and the second normal stress is equal to N2. And these are even functions, but they are 0 at gamma dot equal to 0, because of this particular functional form, you can write this as, so once you have made that particular observation that N1 and N2 must be even functions, you can write them as further N1 of gamma dot, I will write both of these together because actually the exact same expression is there.

So it is an even function, so I can make that even function by, so most likely it suggests that this is gamma dot square and multiplied by some Mu 1 I am not going into the derivation of why it is exactly like this, but I am just trying to physically argue that these will be even functions and so this is a functional form that satisfies that criteria.

So now see whatever be the values where Mu 1 and Mu 2 are two new functions that we have introduced. So N1 and N2 which were the normal stress differences are now being expressed in terms of some Mu 1 and Mu 2 and these two, Mu 1 and Mu 2, so from here we, so we have two functions here. So Mu 1 and Mu 2 are called the first and second normal stress coefficients respectively obviously, normal stress coefficients.

And they are important because they are material properties. Now, the reason we are discussing these normal stress differences is because this is one way in which complex fluids or viscoelastic fluids start to differ from the general, the Newtonian fluids and this leads to very interesting effects and hence they have to be accounted for.

And their normal stress differences now that you are seeing that they are important material properties means that you have, you can use these experimental observations to actually in a sense quantify the fluid.

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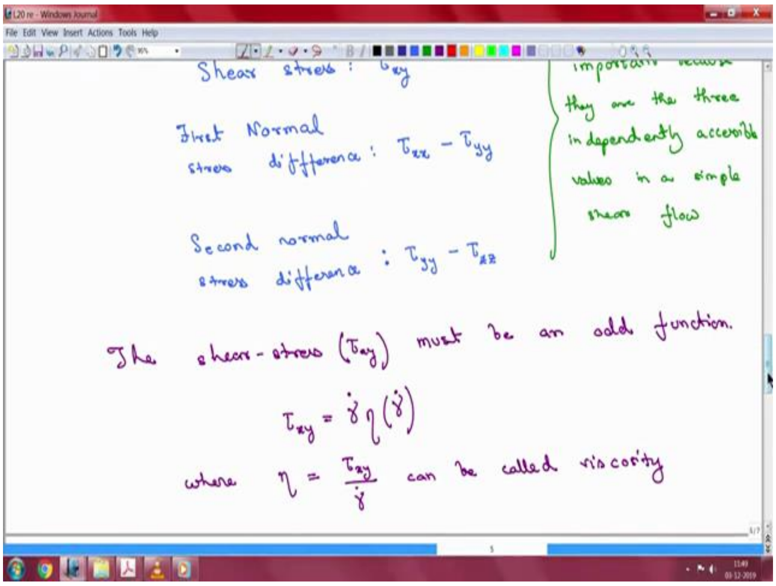

So N1 and N2 are as we had discussed earlier, they are independently accessible, so they are experimentally accessible. So these are quantities that you can measure experimentally. Once you have done that, we have said that these are going to be some values, N1 and N2 and then we further said that these are even functions and this functional form we did not derive but this is, let just assume that this is correct at the moment.

You can look it up later in a more advanced course why this particular functional form. But it is going to gamma dot square multiplied by Mu 1 and Mu 2. So the purpose here was to introduce these two important material functions. And secondary, these normal stress differences do lead to very interesting effects in these fluids and in today's class we are going to discuss a little bit of that.

Just on the same ideas that we were discussing, the non-Newtonian fluids do show some very interesting experimental phenomena which are experimentally observable phenomena, which puts them very apart from Newtonian fluids. And there are many such and one of them, very famous effects is also called Rod climbing effect, or the Weissenberg effect.

So, I am just going to list out some of the classical effects where the behaviour of the Newtonian fluid starts to be in strong contrast to that of non-Newtonian fluids.

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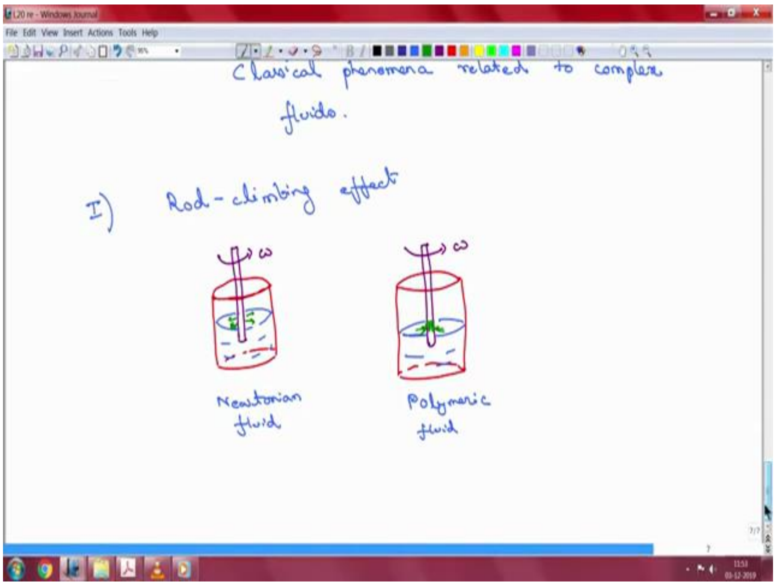

So classical phenomena related to complex fluids and the primary ones that we are going to discuss today is also called the Rod climbing effect. In this effect, what happens is, let us say you start out this, a beaker and in the beaker you have put a rod. This is, let us say a metal rod and you have a fluid. Let me draw this a little bit better.

So this is, the beaker is filled with fluid and what you are going to do is you are going to make this rod rotate at a certain angular frequency. Now if this is a Newtonian fluid, what would happen is the centrifugal forces will force the fluid to flow outward or away from the rod and the meniscus dips a little bit.

So these, actually these are radially outward and the meniscus dips. So this is what you, behaviour you see if you have a beaker full of Newtonian fluid, but let us say you instead have a beaker full of polymeric fluid. So this is Newtonian fluid, this is some polymeric fluid is there. And I am using the example of polymeric fluid deliberately, it did not only be a polymeric fluid, but I will show you an experimental result from our lab, which relates to polymeric fluids, that is why and this effect is nicely visible in that.

If you have a polymeric fluid then under certain conditions what can happen is the flow can start, the polymeric fluid can start moving towards the centre and as a result the meniscus actually starts to rise up this rod and that is why it is called the rod climbing effect. It can be seen for polymeric fluids and for other type of fluids also.

But in our lab, so what Navin and Udita from our lab, they did a very beautiful experiment where they captured this on camera, and I am going to show you some of the results. That is very nice, but this effect is not only restricted to polymeric fluids, but it is possible in other ones, but the reason I am talking about this right after the normal stress difference is because this phenomena is usually linked to the normal stress difference that is present in these kind of fluids.

This effect was first described by I think Garner and Nissan and by another person Russell, but although it was known in the paint industry for quite some time. And then later on, there was a very famous paper by Weissenberg on this particular topic, where he explains this phenomena. And it is this effect, rod climbing effort is also known as the Weissenberg effect because of that.

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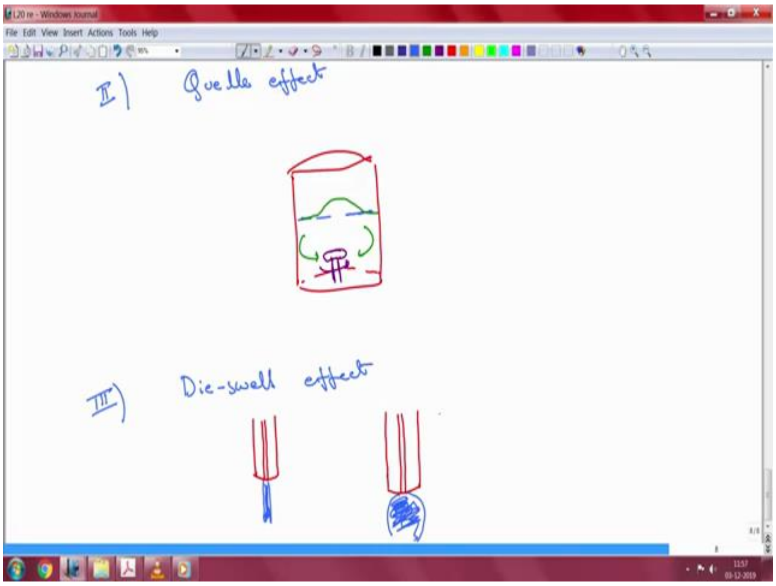

There is another related effect, which is called the Quelle effect and in this system, what you can have is, let us say you have a beaker and instead of rod that is partially immersed, you have let us say, an impeller here inside that is fully submerged and you have fluid in this. Then when you start rotating it, what can happen is you can start to have a bulge here because of secondary flows that can occur in this region.

And this effect is known as the Quelle effect. This is, we do see secondary flows even in our Weissenberg or rod climbing effects system. So we will show you that as well. Now, there are many other classical effects that you might come up. You can, you will probably encounter when you start reading up about non Newtonian fluids and for example, there are other ones which are there, which is for example, this effort called the Die-swell effect.

In the Die-swell effect, what you have is let us say you have fluid coming out of a very thin pipe. If it is a Newtonian fluid, the extrude, the fluid that comes out has a diameter that is almost the same as the inner diameter or the diameter of this particular tube from which it is coming up. But in the case of strongly non Newtonian fluids, what can happen is that there can be a very big bulge in the fluid system as it comes out. And that is why it is also called the Die-swell effect.

Then similar other effects called the elastic recoil and the ubler effect, but we cannot go into all of them. What I would like to do is I want to show you a couple of interesting results from our lab. And I would like to discuss some of the important papers related to that.

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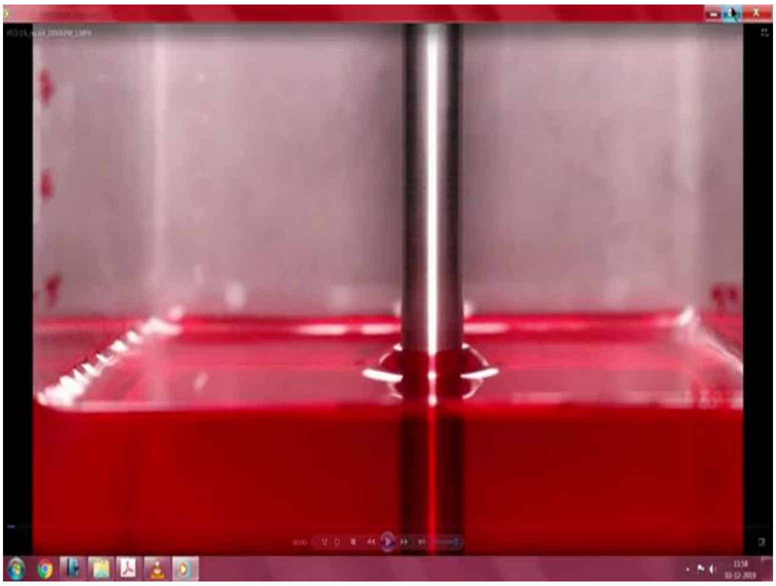

So going back to the rod climbing effect, we as I said, two people from my lab, they did an experiment, Navin and Udita and what you have here is this a rod that is partially immersed, this is a rectangular beaker and you have a polymeric fluid here. So you have a polymeric fluid that is there in the system and this is a rod and we are going to rotate this rod at a particular angular velocity.

Now, this is PEO, polyethylene oxide 1 percent of polyethylene oxide, so we took a powder of polyethylene oxide and we dissolved it in water to create this volume of fluid and it looks red because there is a dye in here for better visualizations. So this that is why it looks red. So let me play this video and then I will explain.

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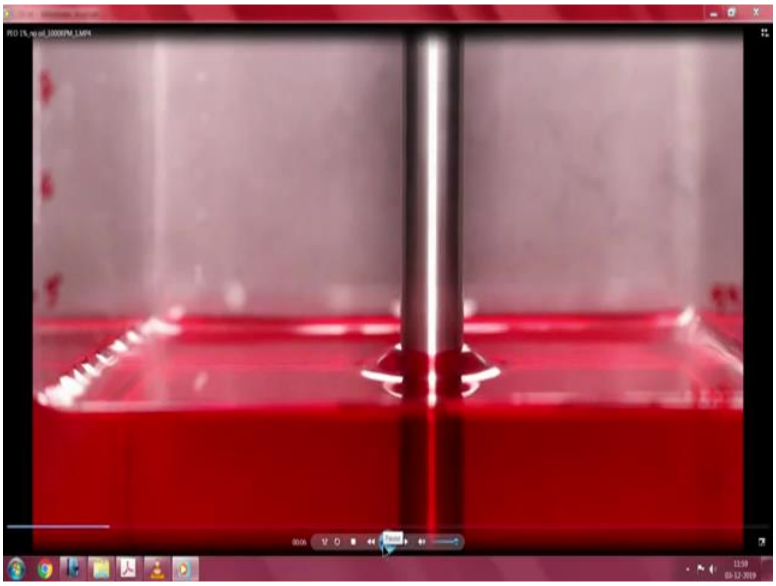

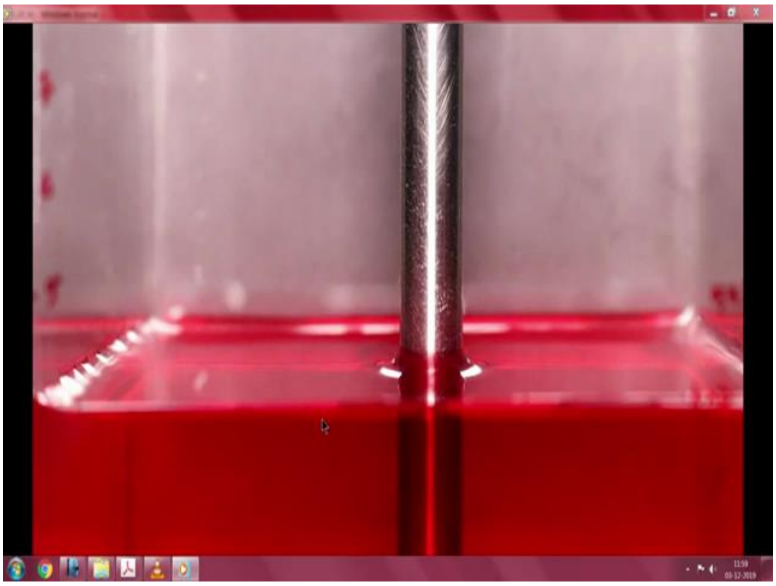

The rod is stationary now and it is going to rotate. So I hope you saw how this meniscus rose here. So this is called the rod climbing effect. If you go to higher polymer concentrations and higher rpms, this effect can become even more drastic. Here I believe the omega is something, so the rod is being rotated at around 1000 rpm and once the rod stops moving, the fluid just goes back to its original rest state.

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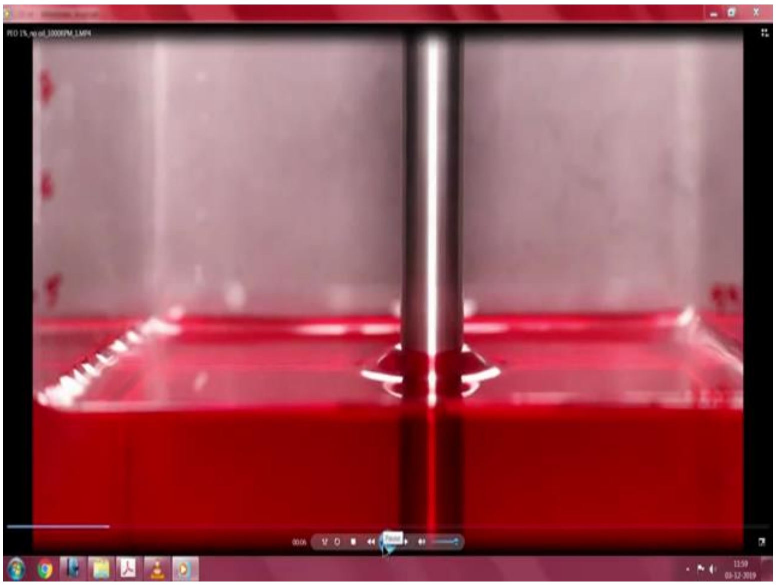

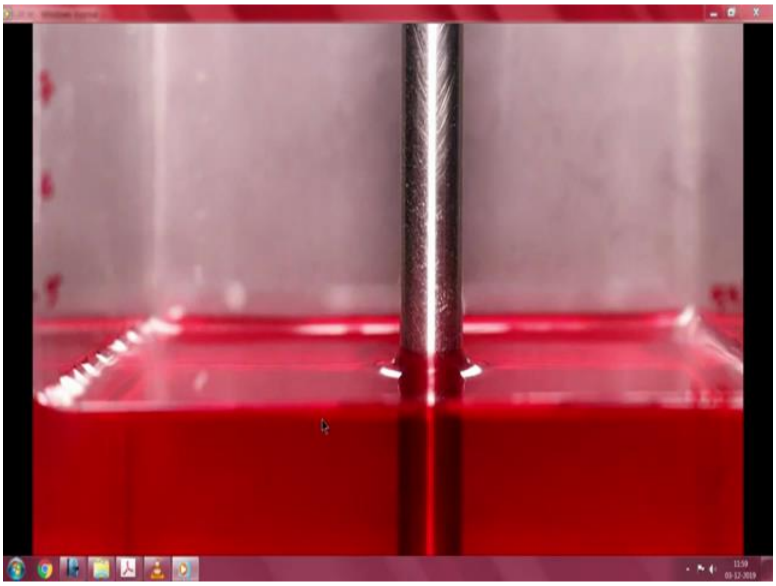

So let us quickly look back at it one more time. What we saw. So this is a fluid at rest, you have the stationary meniscus, which is formed right around the rod and you can see the difference. So you can see clearly this very large rise. So this is the rod climbing effect.

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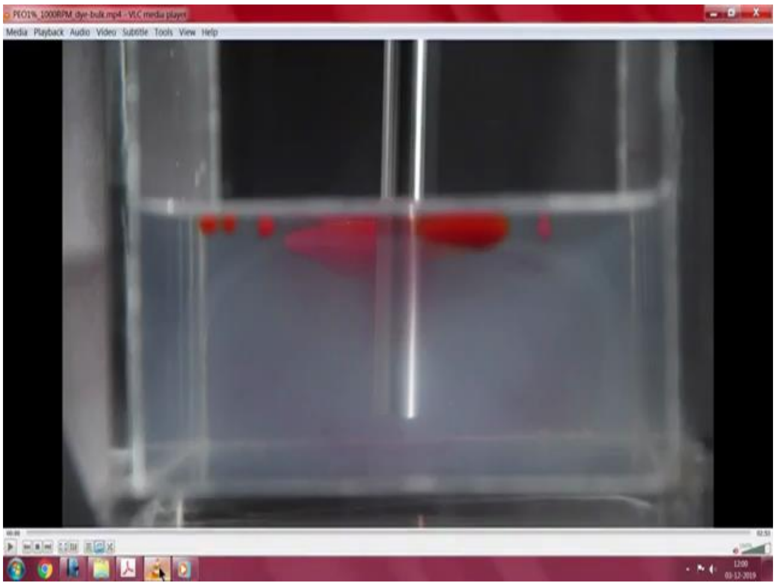

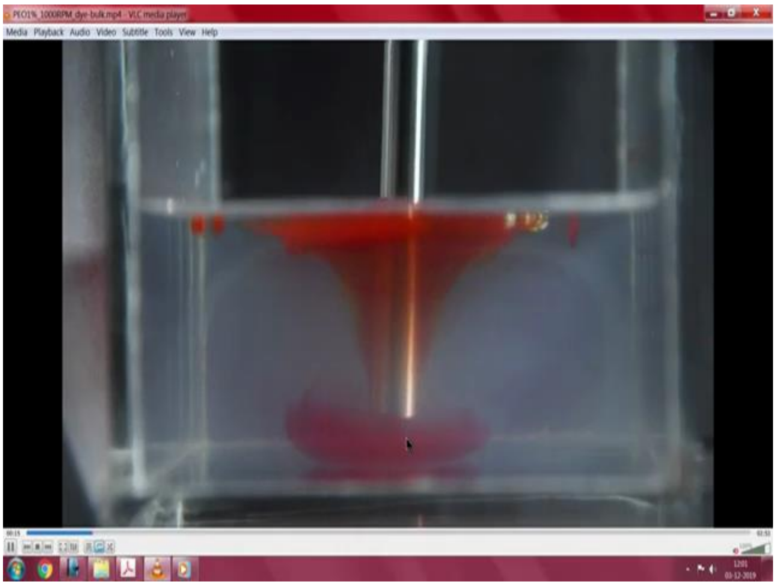

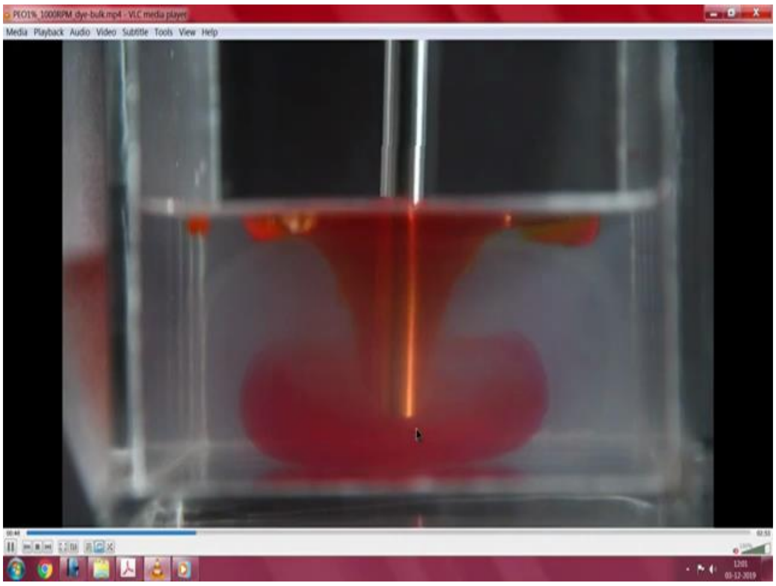

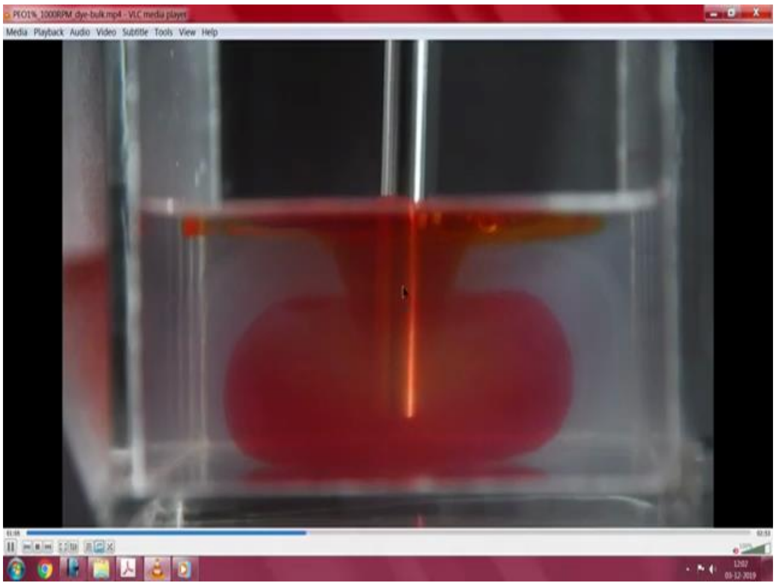

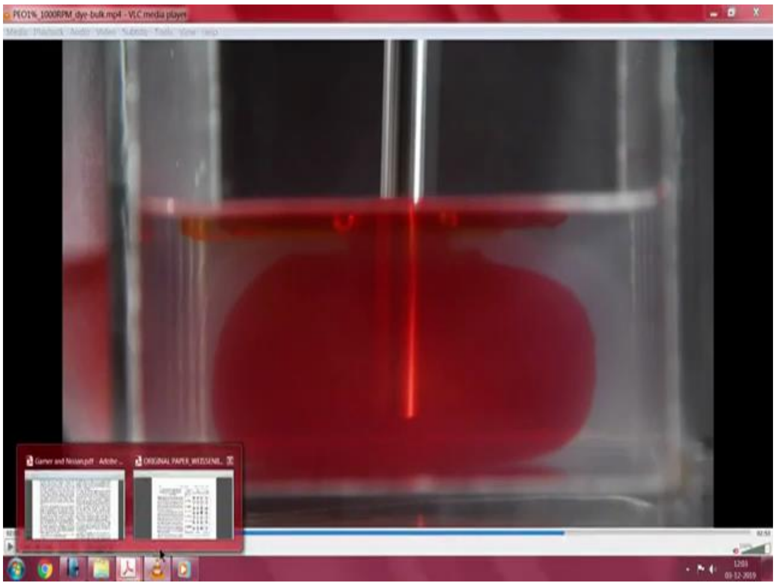

Now, in our lab we did another experiment. So this is a slightly different experiment where the camera was positioned at a different angle. And here this is the original, so this is polyethylene oxide once again. It is colourless in this case because the dye has not been mixed with it and we have the rod which is partially dipping and you can see there is a gap between the rod and the floor right here.

So we are going to start this video. So this is by the way, this is a dye up here. And what I would like you to see is how the dye where the dye gets attracted. So the rod has started rotating and you can see that that dye is slowly coming down, this is a very strong flow and the flow goes here and, so you can see this dye is forming a very beautiful conical shape over here and here, the dye is spreading out slowly because of the fluid flow.

The rod is still rotating by the way. So the dye is slowly spreading to the fluid movement and you do have rod climbing effect right here but because the camera is looking at this whole setup from a different angle, you cannot see that. So, that part is not visible over here. So at the moment you can see only the fluid flow but both of them are happening simultaneously in this experimental system.

And again this video is thanks to Navin and Udita. You can see this video is real time and the periphery of the dye seems to not be moving anymore. It is actually moving and it is moving very very slowly. So it shows that there is a strong recirculation region here. So you can, it will be up to fluid, up to diffusion, partly to take this dye to the other locations. You can see the circular movement at the top.

There are some bubbles which are just moving round and round.

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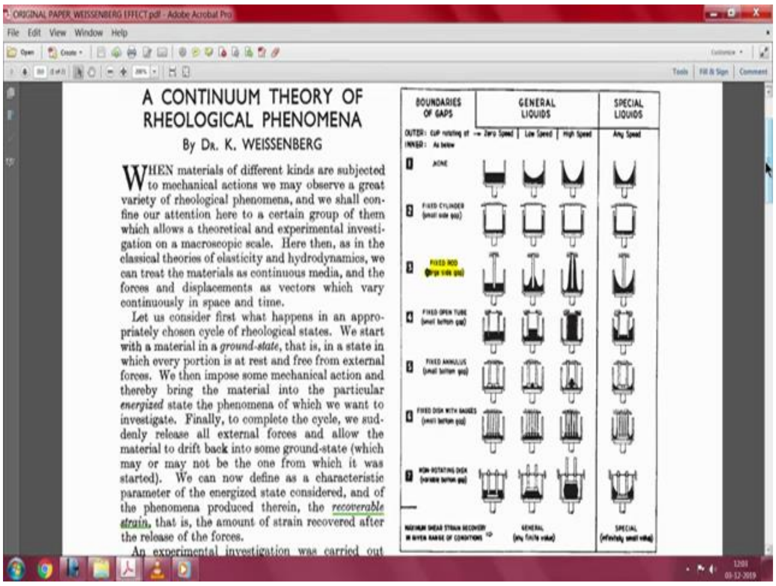

A CONTINUUM THEORY OF RHEOLOGICAL PHENOMENA

By Dr. K. WEISSENBERG

WHEN materials of different kinds are subjected to mechanical actions we may observe a great variety of rheological phenomena, and we shall confine our attention here to a certain group of them which allows a theoretical and experimental investigation on a macroscopic scale. Here then, as in the classical theories of elasticity and hydrodynamics, we can treat the materials as continuous media, and the forces and displacements as vectors which vary continuously in space and time.

Let us consider first what happens in an appropriately chosen cycle of rheological states. We start with a material in a *ground-state*, that is, in a state in which every portion is at rest and free from external forces. We then impose some mechanical action and thereby bring the material into the particular *energized* state the phenomena of which we want to investigate. Finally, to complete the cycle, we suddenly release all external forces and allow the material to drift back into some ground-state (which may or may not be the one from which it was started). We can now define as a characteristic parameter of the energized state considered, and of the phenomena produced therein, the *recoverable strain*, that is, the amount of strain recovered after the release of the forces.

An experimental investigation was carried out

So this effect, so one of the very important papers on this particular topic was written by Weissenberg and that paper is titled a continuum theory of rheological phenomena. It was published in Nature in 1947. And Weissenberg says that when materials of different kinds are subjected to mechanical actions, we may observe a great variety of rheological phenomena and we shall confine our attention here to a certain group of them, which allows a theoretical and experimental investigation on a macroscopic scale.

Here then, as in the classical theories of elasticity and hydrodynamics, we can treat the materials as continuous media and the forces and displacements as vectors which vary continuously in space and time. So he is considering this entire, he is going to consider this entire phenomena from a continuum perspective and that is what he lays down in the introduction.

And then he goes on to say that let us consider first what happens in an appropriate chosen cycle of rheological states. We start with a material in a ground state. That is in a state in which every portion is at rest and free from external forces. So we started our experiment also from the ground state, where everything there was no externally imposed force on the system.

And then we saw that the rod climbing effect happens once the system is not in the, is removed from the ground state. So when we impose some mechanical action. So he also goes on to say, we then impose some mechanical action and thereby bring the material into a particular in a particular energized state, the phenomena of which we want to investigate.

So finally, to complete the cycle, we suddenly release all external forces and allow the material to drift back into some ground state. You can see that this is very similar to the ideas that we had developed at the beginning of the class with the stress relaxation and the stress control tests where we would apply some stress, and then we would release the stress and then we will see what happens.

So it is a very, very similar idea to what he is discussing over here. And he goes on to discuss about recoverable strains, etc. This couple of important things I would like to note and it is this particular figure. So here he says flow of liquids under the actions of stationary shear in gaps. And he goes on to list a many different types of experimental conditions.

The one that is particularly valid for us is this particular number 3, where we have this beaker and then we have this rod that is immersed, partially immersed into the fluid, and we would have this rod climbing effect. And it shows that under very high, for example, this is the ground state and this is the low speed state and at very high speed states, you can also have a very, very strong rod climbing effect that you can see.

So, he goes on to list many other cases over here. So this manuscript, if you wish, you can take a look at.

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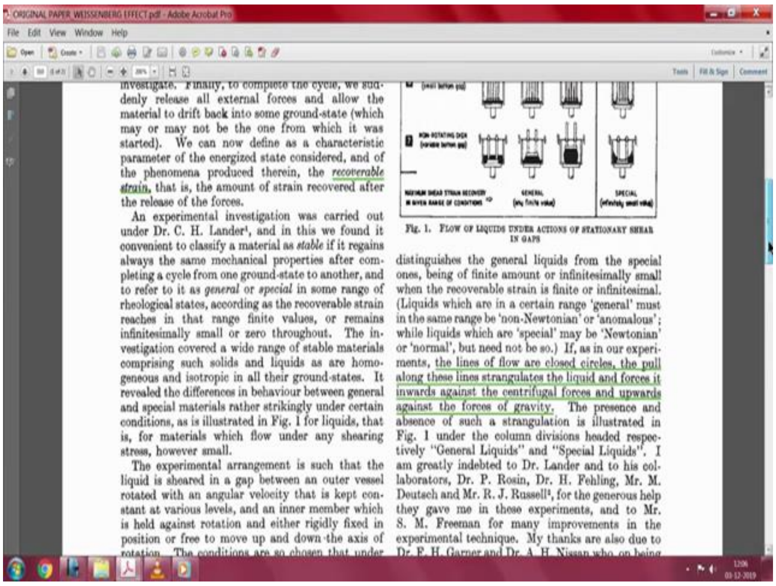

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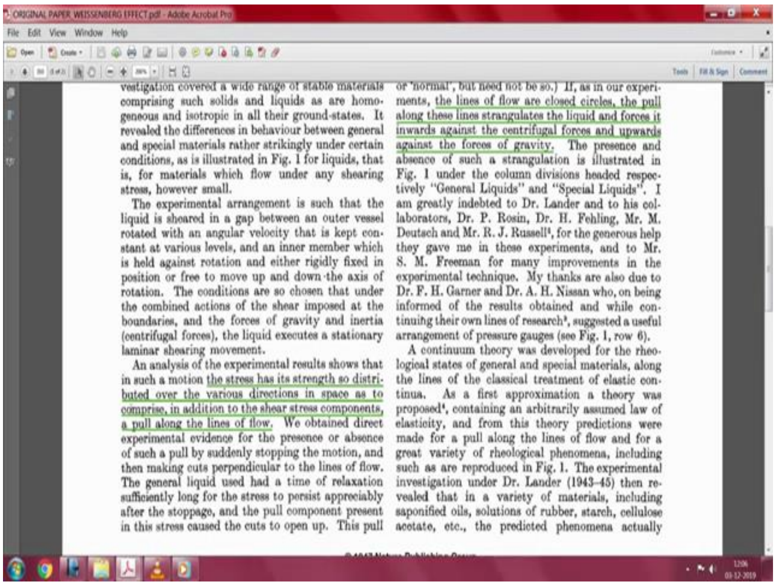
investigate. Finally, to complete the cycle, we suddenly release all external forces and allow the material to drift back into some ground-state (which may or may not be the one from which it was started). We can now define as a characteristic parameter of the energized state considered, and of the phenomena produced therein, the *recoverable strain*, that is, the amount of strain recovered after the release of the forces.

An experimental investigation was carried out under Dr. C. H. Lander[1], and in this we found it convenient to classify a material as *stable* if it regains always the same mechanical properties after completing a cycle from one ground-state to another, and to refer to it as *general* or *special* in some range of rheological states, according as the recoverable strain reaches in that range finite values, or remains infinitesimally small or zero throughout. The investigation covered a wide range of stable materials comprising such solids and liquids as are homogeneous and isotropic in all their ground-states. It revealed the differences in behaviour between general and special materials rather strikingly under certain conditions, as is illustrated in Fig. 1 for liquids, that is, for materials which flow under any shearing stress, however small.

The experimental arrangement is such that the liquid is sheared in a gap between an outer vessel rotated with an angular velocity that is kept constant at various levels, and an inner member which is held against rotation and either rigidly fixed in position or free to move up and down the axis of rotation. The conditions are so chosen that under

Fig. 1. Flow of liquids under actions of stationary shear in gaps

distinguishes the general liquids from the special ones, being of finite amount or infinitesimally small when the recoverable strain is finite or infinitesimal. (Liquids which are in a certain range 'general' must in the same range be 'non-Newtonian' or 'anomalous'; while liquids which are 'special' may be 'Newtonian' or 'normal', but need not be so.) If, as in our experiments, the lines of flow are closed circles, the pull along these lines strangulates the liquid and forces it inwards against the centrifugal forces and upwards against the forces of gravity. The presence and absence of such a strangulation is illustrated in Fig. 1 under the column divisions headed respectively "General Liquids" and "Special Liquids". I am greatly indebted to Dr. Lander and to his collaborators, Dr. P. Rosin, Dr. H. Fehling, Mr. M. Deutsch and Mr. R. J. Russell[1], for the generous help they gave me in these experiments, and to Mr. S. M. Freeman for many improvements in the experimental technique. My thanks are also due to Dr. F. H. Garner and Dr. A. H. Nissan who on being



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vestigation covered a wide range of stable materials comprising such solids and liquids as are homogeneous and isotropic in all their ground-states. It revealed the differences in behaviour between general and special materials rather strikingly under certain conditions, as is illustrated in Fig. 1 for liquids, that is, for materials which flow under any shearing stress, however small.

The experimental arrangement is such that the liquid is sheared in a gap between an outer vessel rotated with an angular velocity that is kept constant at various levels, and an inner member which is held against rotation and either rigidly fixed in position or free to move up and down the axis of rotation. The conditions are so chosen that under the combined actions of the shear imposed at the boundaries, and the forces of gravity and inertia (centrifugal forces), the liquid executes a stationary laminar shearing movement.

An analysis of the experimental results shows that in such a motion the stress has its strength so distributed over the various directions in space as to comprise, in addition to the shear stress components, a pull along the lines of flow. We obtained direct experimental evidence for the presence or absence of such a pull by suddenly stopping the motion, and then making cuts perpendicular to the lines of flow. The general liquid used had a time of relaxation sufficiently long for the stress to persist appreciably after the stoppage, and the pull component present in this stress caused the cuts to open up. This pull

or 'normal', but need not be so.) If, as in our experiments, the lines of flow are closed circles, the pull along these lines strangulates the liquid and forces it inwards against the centrifugal forces and upwards against the forces of gravity. The presence and absence of such a strangulation is illustrated in Fig. 1 under the column divisions headed respectively "General Liquids" and "Special Liquids". I am greatly indebted to Dr. Lander and to his collaborators, Dr. P. Rosin, Dr. H. Fehling, Mr. M. Deutsch and Mr. R. J. Russell[1], for the generous help they gave me in these experiments, and to Mr. S. M. Freeman for many improvements in the experimental technique. My thanks are also due to Dr. F. H. Garner and Dr. A. H. Nissan who, on being informed of the results obtained and while continuing their own lines of research[3], suggested a useful arrangement of pressure gauges (see Fig. 1, row 6).

A continuum theory was developed for the rheological states of general and special materials, along the lines of the classical treatment of elastic continua. As a first approximation a theory was proposed[4], containing an arbitrarily assumed law of elasticity, and from this theory predictions were made for a pull along the lines of flow and for a great variety of rheological phenomena, including such as are reproduced in Fig. 1. The experimental investigation under Dr. Lander (1943–45) then revealed that in a variety of materials, including saponified oils, solutions of rubber, starch, cellulose acetate, etc., the predicted phenomena actually

There are couple of important lines that I would like to draw your attention to. Over here for example, he will attribute this partially to the normal stress. So he says that an analysis of the experimental results shows that in such a motion, the stress has its strength so distributed over the various directions in space, as to comprise in addition to the shear stress components, a pull along the lines of the flow.

And then furthermore, he goes on to say here that if as in our experiments, the lines of flow are closed circles, the pull along these lines strangulates the fluid, the liquid and forces it inwards against the centrifugal forces and upward against the forces of gravity. So he is trying to explain the phenomena.

Our purpose here is not to go into a whole lot of detail into the exact mechanics of this because that would require understanding the exact nature of forces and deriving the condition, all that, but I wish to give you a good introduction and show you some of the important manuscripts of this area. So you can look at it yourself.

The other important, as I said, just before that before him, there was another couple of gentlemen who had performed very good experiments, and they had talked about this particular phenomena, and that is Garner and Nissan and you can see that in this article, he actually thanks Garner and Nissan and he says, Dr. Garner and Nissan who on being informed of the results obtained and while continuing their own lines of research suggested a useful arrangement of pressure gauges. Anyway, so let us quickly look at Garner and Nissan's paper as well.

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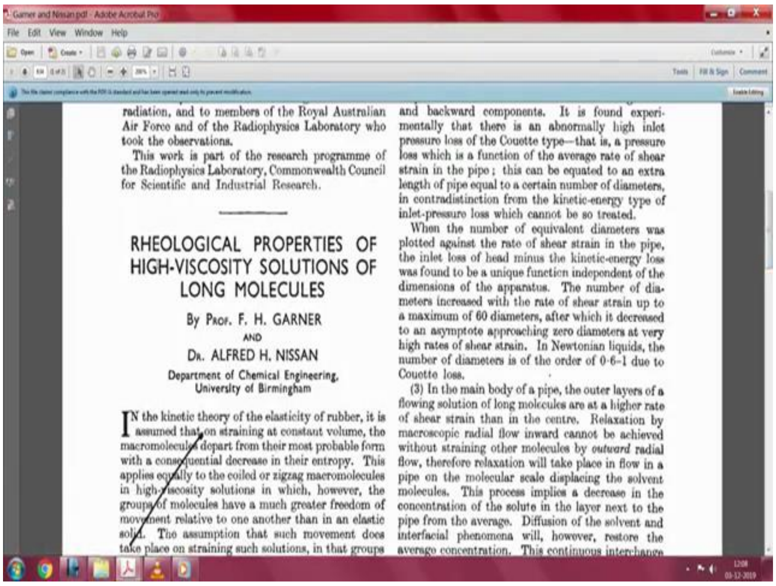

radiation, and to members of the Royal Australian Air Force and of the Radiophysics Laboratory who took the observations.

This work is part of the research programme of the Radiophysics Laboratory, Commonwealth Council for Scientific and Industrial Research.

RHEOLOGICAL PROPERTIES OF HIGH-VISCOSITY SOLUTIONS OF LONG MOLECULES

By Prof. F. H. GARNER AND Dr. ALFRED H. NISSAN

Department of Chemical Engineering, University of Birmingham

IN the kinetic theory of the elasticity of rubber, it is assumed that on straining at constant volume, the macromolecules depart from their most probable form with a consequential decrease in their entropy. This applies equally to the coiled or zigzag macromolecules in high-viscosity solutions in which, however, the groups of molecules have a much greater freedom of movement relative to one another than in an elastic solid. The assumption that such movement does take place on straining such solutions, in that groups

and backward components. It is found experimentally that there is an abnormally high inlet pressure loss of the Couette type—that is, a pressure loss which is a function of the average rate of shear strain in the pipe; this can be equated to an extra length of pipe equal to a certain number of diameters, in contradistinction from the kinetic-energy type of inlet-pressure loss which cannot be so treated.

When the number of equivalent diameters was plotted against the rate of shear strain in the pipe, the inlet loss of head minus the kinetic-energy loss was found to be a unique function independent of the dimensions of the apparatus. The number of diameters increased with the rate of shear strain up to a maximum of 60 diameters, after which it decreased to an asymptote approaching zero diameters at very high rates of shear strain. In Newtonian liquids, the number of diameters is of the order of 0·6–1 due to Couette loss.

(3) In the main body of a pipe, the outer layers of a flowing solution of long molecules are at a higher rate of shear strain than in the centre. Relaxation by macroscopic radial flow inward cannot be achieved without straining other molecules by *outward* radial flow, therefore relaxation will take place in flow in a pipe on the molecular scale displacing the solvent molecules. This process implies a decrease in the concentration of the solute in the layer next to the pipe from the average. Diffusion of the solvent and interfacial phenomena will, however, restore the average concentration. This continuous interchange

So Garner and Nissan's paper was titled Rheological Properties Of High Viscosity Solutions Of Long Molecules. So these are the macromolecules that we had talked about, and this had appeared in nature but a year ago, 1946 is the year of publication. And if you want, you can go through this manuscript yourself.

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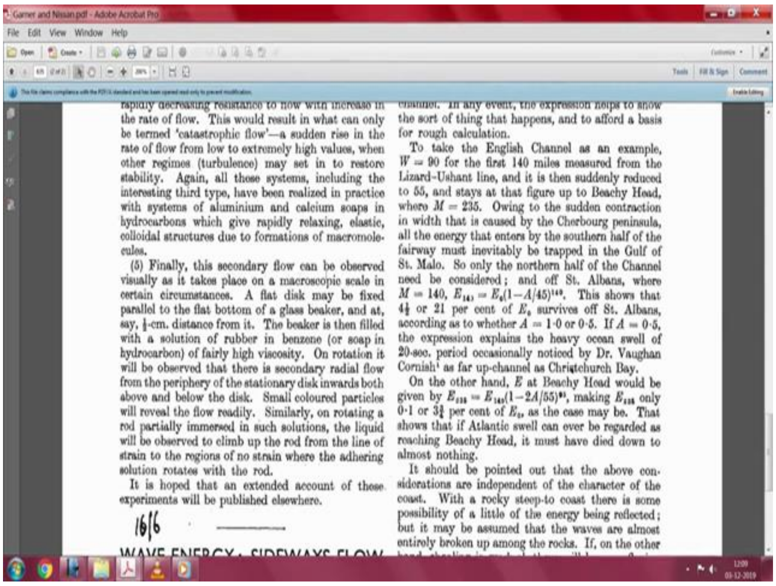
rapidly decreasing resistance to flow with increase in the rate of flow. This would result in what can only be termed 'catastrophic flow'—a sudden rise in the rate of flow from low to extremely high values, when other regimes (turbulence) may set in to restore stability. Again, all these systems, including the interesting third type, have been realized in practice with systems of aluminium and calcium soaps in hydrocarbons which give rapidly relaxing, elastic, colloidal structures due to formations of macromolecules.

(5) Finally, this secondary flow can be observed visually as it takes place on a macroscopic scale in certain circumstances. A flat disk may be fixed parallel to the flat bottom of a glass beaker, and at, say, ½-cm. distance from it. The beaker is then filled with a solution of rubber in benzene (or soap in hydrocarbon) of fairly high viscosity. On rotation it will be observed that there is secondary radial flow from the periphery of the stationary disk inwards both above and below the disk. Small coloured particles will reveal the flow readily. Similarly, on rotating a rod partially immersed in such solutions, the liquid will be observed to climb up the rod from the line of strain to the regions of no strain where the adhering solution rotates with the rod.

It is hoped that an extended account of these experiments will be published elsewhere.

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WAVE ENERGY: SIDEWAYS FLOW

channel. In any event, the expression helps to show the sort of thing that happens, and to afford a basis for rough calculation.

To take the English Channel as an example, $W = 90$ for the first 140 miles measured from the Lizard-Ushant line, and it is then suddenly reduced to 55, and stays at that figure up to Beachy Head, where $M = 235$. Owing to the sudden contraction in width that is caused by the Cherbourg peninsula, all the energy that enters by the southern half of the fairway must inevitably be trapped in the Gulf of St. Malo. So only the northern half of the Channel need be considered; and off St. Albans, where $M = 140$, $E_{140} = E_0(1-A/45)^{140}$. This shows that 4½ or 21 per cent of E_0 survives off St. Albans, according as to whether $A = 1{\cdot}0$ or $0{\cdot}5$. If $A = 0{\cdot}5$, the expression explains the heavy ocean swell of 20-sec. period occasionally noticed by Dr. Vaughan Cornish[1] as far up-channel as Christchurch Bay.

On the other hand, E at Beachy Head would be given by $E_{235} = E_{140}(1-2A/55)^{95}$, making E_{235} only 0·1 or 3¾ per cent of E_0, as the case may be. That shows that if Atlantic swell can ever be regarded as reaching Beachy Head, it must have died down to almost nothing.

It should be pointed out that the above considerations are independent of the character of the coast. With a rocky steep-to coast there is some possibility of a little of the energy being reflected; but it may be assumed that the waves are almost entirely broken up among the rocks. If, on the other

I just would like to draw your attention to one of the final paragraphs here, where they talk about the secondary flow. And they say that this is observation number 5 that finally, the secondary flow can be observed visually as it takes place on a macroscopic scale in certain circumstances.

A flat disk maybe fixed parallel to the flat bottom of the glass beaker at say half centimetre distance from it. The beaker is then filled with a solution of rubber in benzene or soap in hydrocarbon of fairly high viscosity. On rotation it can be observed there is a secondary, radial flow from the periphery of the stationary disk inwards, both above and below the disk.

Small coloured particles will reveal the flow readily. Similarly, on rotating a rod partially immersed in such solutions, the liquid will be observed to climb up the rod from the line of the strain to the regions of no strain. So here, he is also discussing the rod climbing effect. So these are some of the original manuscripts of this area and you are welcome to download these and take a look at this in more detail at your leisure.

In the next class, what we are going to do is we are going to head on into the lab. So today we had a mix of looking at some of the experimental results and theoretical constructs that are relevant, and in the next class, we will go into the lab and start doing some nice experiments for ourselves. So the next class is going to have a lab component. So we will end our class today here. Thank you very much.