**Rheology and Processing of Paints, Plastic and Elastomer based Composites**
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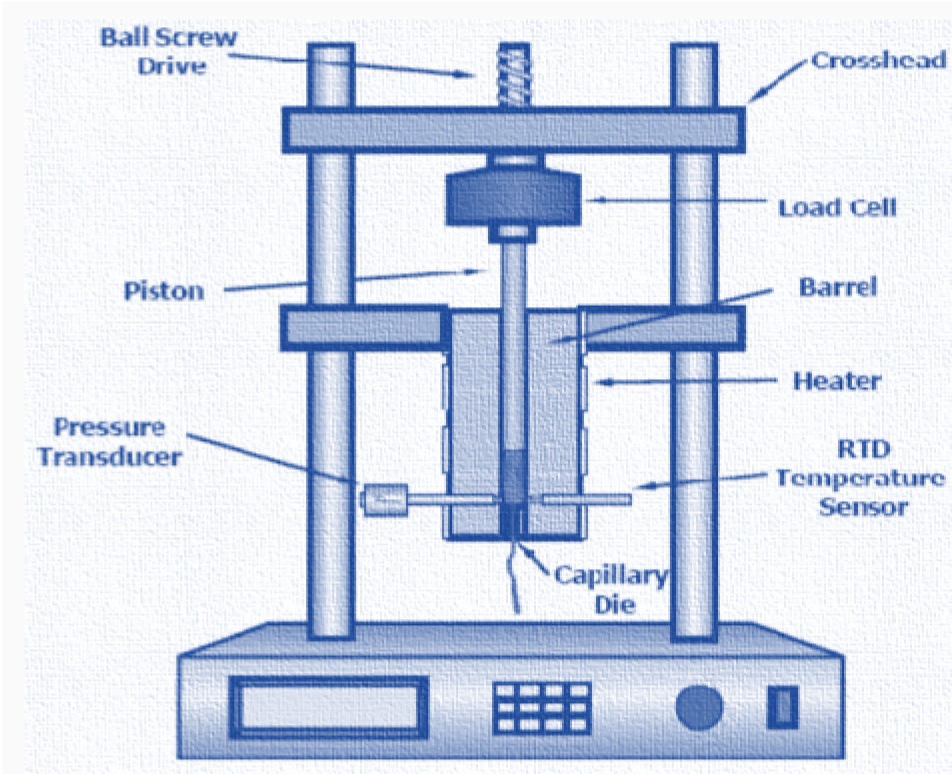
# Lecture 13
# Capillary Rheometer

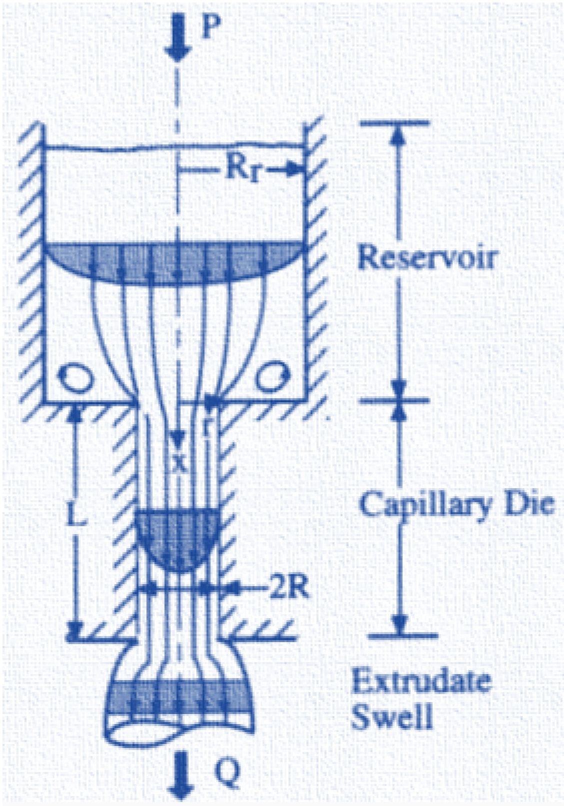
Welcome to NPTEL online certification courses on Rheology and Processing of Pents, Plastic and Elastomer-based Composites. Today we are in week number 3 and the first lecture of week number 3, 3.1 is on Capillary Rheometer. So, concepts covered will be the capillary rheometer, its anatomy, shear stress and velocity profile from Navier-Stokes equations, shear rate and its Rabinowitsch correction, Bagley corrections in a capillary rheometer, Mooney correction for ball slip, normal stress differences for die swell and surface roughness. So, the keyword once again I am not naming each and every one, you just go through the list that includes stress, shear stress, shear rate, rotational rheometer, Navier-Stokes by SLE equation, stress relaxation etcetera etcetera, this is for your study purpose to quickly assess those. So, so far I talked about the rotational rheometers and the limitation of it was of course, limited by the range of shear rates it covers.

So, you cannot go very very extreme high shear rate you cannot cover, but most of the polymer processing including extrusion say, transfer molding, transfer molding it happens at a shear rate around 100s or 200s second inverse, extrusion of the tune of 1000 second inverse or more and when you talk about injection modeling it is of the tune of 10,000 second inverse. So, as you can understand from here, if I have only capillary rheometric data maybe we have more I mean hold on the viscoelastic behavior or its elastic and viscous component of it directly you can measure normal force difference those are the few of the advantages you have in you know rotational rheometers, but at the same time it really really does not give you the you know high shear rate behavior. Of course, as I told you, you can use some principles like Cox-merz principle to try to extrapolate it, but nonetheless unless you have a more of experimental data I mean it may not be realistic in the sense because Cox-merz principle also has certain limitations as I mentioned is a special at high shear rate there will be edge for fracture. So, that essentially does not give the real you know viscosity data across the shear rate.




So, let us try to understand what is the capillary rheometer or capillary viscometer also it is said. So, very very common device measuring viscosity. So, gravity, compressor, compress gas or a piston is used to generate a pressure is just like a you know just like a mimicking extrusion basically. A capillary tube of radius r or length l is connected to the bottom of a reservoir you have a reservoir over which there is a piston that will compress the fluid you heat the fluid and then you try to force it through the you know capillary. And the force on the piston or pressure which is which amounts to the shear stress and the flow rate that is the volumetric flow rate you are getting these are the two major component that get immediately out of it.

And the capillary rheometer as I said is used for determining viscosities of material at high shear rates high means how high it is. It can be 10 to generally speaking 10 to you know 10,000 or even more 10 to the power 5, 10 to the power 6 second inverse that data can be obtained. So, it covers pretty well most of the processing that is involves in plastic, rubber or fibers say for example, that means starting from your molding techniques like injection transfer also it covers blow molding I mean even the reaction injection molding so on and so forth. So, the looking at the anatomy as simple as it that as it is you have a piston and that pistons basically forces the polymer which is compacted on the you know reservoir of it. And then it enters this narrow gap narrow you know cylindrical you know passage which is called capillary.




And finally, it extrudes out and there is a laser assembly which will directly measure the you know what is the dimensional changes or die swell of it. Then of course, you can look into the surface of it doing some spectrographic, I mean electron microscopic or optical microscopic evaluation of it. So, what essentially it measures the volumetric flow rate as I said as well as there is a pressure transducer that measures the pressure there. And now of course, you have a RTD sensor which measures exactly what is the temperature while extruding. So, this entire assembly is as simple as that.

**Recall from Fluid Mechanics**

We can record force on piston, F (or the pressure drop ΔP), and volumetric flow rate, Q

- **Shear stress profile inside the tube:**

eq. (1)

$$\tau = \frac{r}{2}\left(\frac{\Delta P}{L}\right) \qquad \text{At the wall (r=R):} \quad \tau_W = \frac{R}{2}\left(\frac{\Delta P}{L}\right)$$

- **The velocity profile from the Navier-Stokes Equations is:**

$$u(r) = \frac{\Delta P\, R^2}{4\mu L}\left[1 - \left(\frac{r}{R}\right)^2\right]$$

- **Hagen-Poiseuille law for the pressure-driven flow of Newtonian fluids inside a tube:**

$$\Delta P = \mu L \frac{8Q}{\pi} R^{-4}$$

But of course, so when you put it through the piston, the piston can be programmed in such a way that it can go at different velocities. So, by different velocities at different zones it can try to understand if you have a reservoir here that reservoir virtually you make it 6, 7, 8 zones. And in different zones it traverses with different velocity so that you generate a different shear rate there. So, that way you can have a whole range of shear rate and that you can program. And of course, so in while doing that you have a laser assembly that optical images what is the diameter of the extruded and you can have a two lasers one immediately after extrusion another after relax.

- **Shear rate:**

**This is true shear rate for Newtonian fluids but an apparent shear rate for Non-Newtonian fluids.**

$$\dot{\gamma} = \frac{du}{dr} = \frac{\Delta P}{2\mu L} R = \frac{4Q}{\pi R^3} = \dot{\gamma}_{apparent}$$

**For non-Newtonian fluids, if we use the apparent shear rate then we can only calculate an Apparent Viscosity:**

$$\eta_{app} = \frac{\tau_w}{\dot{\gamma}_{app}}$$

- **For non-Newtonian fluids, the Rabinowitsch analysis is as followed:**
- **From the definition of the volumetric flow rate through a tube:**

$$Q = 2\pi \int_0^R r\, u(r)\, dr \xrightarrow{\text{integrating by parts}} Q = \pi r^2 u \Big|_0^R - \int_0^R \pi r^2 \left(\frac{du}{dr}\right) dr$$

- **Applying the "no-slip" boundary condition and eliminating r with the aid of eq. (1)**

$$\frac{\tau_W^3 Q}{\pi R^3} = \int_0^{\tau_W} \tau^2 \left(\frac{du}{dr}\right) d\tau$$

So, relaxed di-sual and running di-sual these are the two data you get it immediately out of it and you know the capillary diameter. This particular capillary it can have a variegated length, variegated diameter so that I mean it can be used up as I will be mentioning that for various correction purpose as well as you know try to imagine if your L by D ratio is very high, then it will have a smooth flow to the capillary. So, entrance and exit effect will be practically I mean it does not have that much of influence. Unlike if you have a very small die so entrance and exit will influence so how to do corrections. So, in order to do those corrective measurements you may have to play with different L by D ratio die.

Having same diameter variegated you know L by D ratio and in some cases while determining the wall slip say for example, correcting the wall slip you may have to do different diameter but same L by D ratio. So, those dies are actually available with precise diameter, precise L by D ratio. So, that is another part of the story I will explain you later. So, what is the advantage? Once again I will highlight here this is the major advantage. Even though if I compare side by side with the you know rotational rheometer, like parallel plate or cone and plate in parallel plate you get directly the first normal force difference.

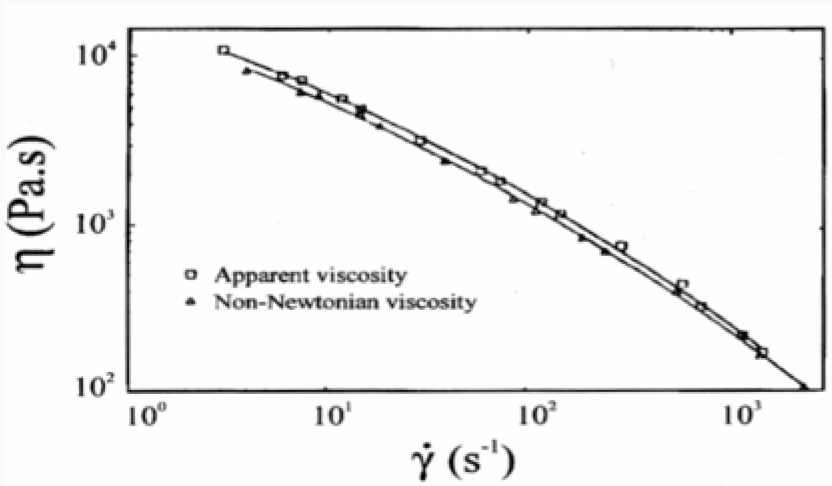
Second normal force difference also you can calculate. But here in this case mostly the normal force differences are indirectly calculated from you know from the relaxation phenomena and so on and so forth. So, that I am not going to cover right away but I will talk as on when it is necessary. So, it may be and this particular geometer very close to the you know processing situation say extrusion as I mentioned. Injection say for example, when you push the polymer through a very narrow nozzle so screw.

So, this particular geometer resembles well with the processing that you actually practically do well shaping operation of that polymers. So, disadvantages unlike in rotational geometer where you took care of the uniform shear rate say for example, it may not be that uniform. It will give you a gross measurement of that number 1. Number 2 wall slip of course, we will be able to correct it but wall slip is a phenomena that will happen occasionally. You can pretty much you know minimize it the wall slip by a serrated sandblasted type of a die although I did not talk about much during that context but that can be very practically taken care of.

Here you cannot avoid it but you can estimate and correct it basically in capillary geometer. Melt fracture is another phenomena because its high shear rate it will always accompanied with the melt fracture. So, and it is very difficult to clean unless you clean it one material to the other you do the same the measurements in that there will be chances of contamination there. So, once again just try to have a diagram of it diagrammatically. So, this is the reservoir this is the piston with the pressure P is pressurizing it and then you see the fluid flow and had it been a you know Newtonian fluid you all I mean what you can anticipate its going to be parabolic velocity profile that is pretty much shown here.

- **After several manipulations, we obtain the Rabinowitsch equation:**

$$\dot{\gamma}_W = \frac{4Q}{\pi R^3}\left(\frac{3}{4} + \frac{1}{4}\frac{d \ln Q}{d \ln \tau_W}\right) = \dot{\gamma}_{app}\left(\frac{3}{4} + \frac{1}{4}\frac{d \ln Q}{d \ln \tau_W}\right)$$




- **The Real Viscosity of the polymer melt is:**

$$\eta = \frac{\tau_W}{\dot{\gamma}_W}$$

But most importantly the transition from the reservoir to you know the capillary that is most important you have if you have this type of a flat entrances from reservoir to capillary there can be vortexes possible. So, practically a polymer moves around some part of that. So, during that course of the journey if it is a reactive polymer rubber thermosetting resin it may get prematurely crossing there that chances are there. So, that is a different context, but ultimately what we are going to monitor this transition from the reservoir to the end this is the die end where I measure the Q, Q is nothing but the volumetric flow rate and R is the diameter of it I mean 2R is the diameter of it R is the radius and L is the length. So, L by D ratio is very very important and coming to the context shortly.

So, closely our attention will be to that particular part of the drawing here. So, what we are ultimately interested in is a force on the piston and that gives me the pressure drop del P and the volumetric flow rate. As I mentioned you earlier these two parameters are at most important while doing any geometry basically ultimately what we are concerned what is the pressure difference across the capillary P1 minus P2 and of course what is the volumetric flow rate I am getting it. And if you recall this MFI what I talked about actually operates in the same principle, but here you have a transducer which measures the pressure precisely and you have a program velocity of the piston that enables you to capture a wide range of shear rate and shear stress of course. So, that is the beauty of a capillary geometer again what I told you just quickly recall.

If you have a capillary flow as I mentioned flow through a cylinder. So, you can pretty well calculate from the pressure drop the shear stress wall shear stress tau equals to R by 2 into del P by L. So, at the wall when R equals to capital R. So, then it turns out to be tau wall equals to R by 2 delta P by L. So, that is what the you can directly from the pressure drop and with the geometry of the capillary you can calculate out shear stress at the wall.

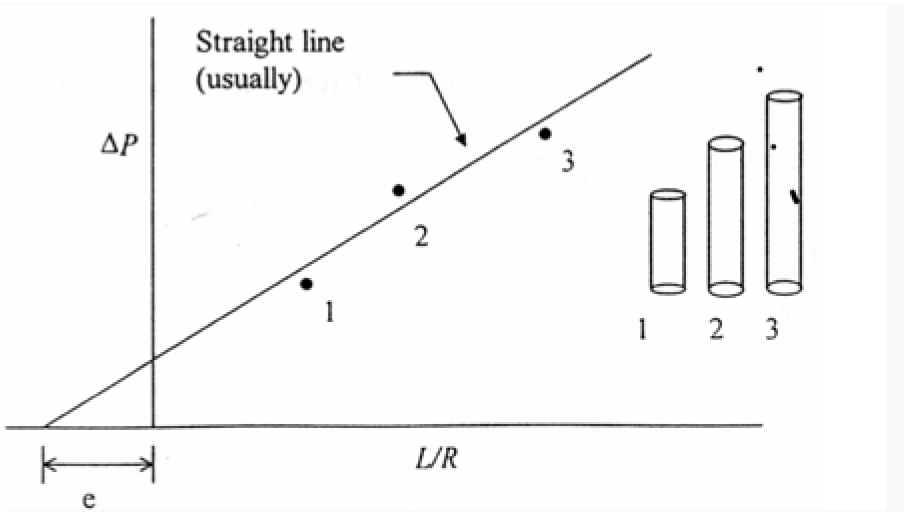
So, this is the first equation. So, you can do from Poiseuille or Navier-Stokes equations. You solve it for a Newtonian fluid ultimately the what velocity profile the parabolic profile I showed you the velocity lines this is the wall this is the wall and at the center always there will be highest velocity and that you solve that velocity and this is the average velocity equation and it is nothing but delP, R square by 4 mu L mu is the viscosity into 1 by R minus R square. So, this signifies the parabolic flow basically. So, Hagen-Poiseuille's law for the pressure driven flow in a Newtonian tube you all know it is nothing but del P amounts to you know mu L into 8 Q by pi into R to the power minus 4.

So, this is the relation where directly your volumetric flow rate that you estimate here is related to del P 1 minus P 2 here. So, that is the relationship holds good from the you directly get it from Hagen-Poiseuille's equation. So, what about the another parameter? We already have estimated wall shear stress. If you recall I will go back this is the wall shear stress whole thing and then what next we have to estimate in order to assess the viscosity of it is a shear rate. So, shear rate is gamma dot equals to du dr velocity gradient equals to del P by into R into 2 into mu L and that amounts to 4 Q into pi R Q.

So, directly from the volumetric flow rate you can get the apparent you know shear rate. So, why am I saying apparent? Because this is the true shear rate for the Newtonian fluids, but it pretty much changes with the you know non-Newtonian fluids and that is why in order to have a you know true shear rate wall shear rate or shear stress you have to do a correction here and that is what is very much necessary from apparent to true for non-Newtonian fluids. So, apparent is physically whatever in wall stress and this apparent shear rate you are getting just you just divide it. So, that is what is the apparent viscosity you call it. I am sorry that many a times I have used the abbreviation eta and sometimes we have used mu, but as I mentioned it to you at the beginning you just assume all the way same it is the viscosity essentially and mu is of course the absolute viscosity here.

So, for a non-Newtonian fluid as I mentioned revenue is analysis is actually I am not going into the details derivation of it, but it actually you will get it you refer to try to see volumetric flow through a tube from that I mean this is the volumetric flow you integrate it is nothing but it is a cylinder you flow you take a small volume element and try to integrate across this radius this is 0 to R this is 0 this is R. So, if you do the integration of it a small volume element R into U R into d R is a volume element and you integrate by parts you end up having Q equals to in that form. So, you know do you this two are actually two variables you try to integrate it and you end up having pi R square into U which is boundary limit is 0 to R and integration 0 to R again the other part of it. So, if you just apply into this equation no slip boundary conditions. So, ultimately you end up having an equation which is nothing but this is the equation this is sometimes called Avinashis equation also basically tau Q into Q by pi R Q equals to integration 0 to you know tau valve this is a valve shear stress into tau S square d U d R into d tau basically.

But do not get confused you just say equation seems to be very long, but ultimately the effective measures you have to do it is very simple. So, this is the valve shear stress and that ultimately revenue equation takes this form this looks little complicated, but nonetheless if you just try to correct it you get a you know this is a true valve shear rate basically. And then from that if you divide this corrected one you get a viscosity as I mentioned it to you. So, if you see apparent one the box one is the apparent and if you have a small little correction though with that correction you get the non Newtonian viscosity or it is a corrected viscosity basically. So, that is how your data needs little processing using revenue equation to get it from apparent to absolute or corrected one basically it is not absolute though it is corrected one.




So, that is what now you get the tau value which is nothing but tau W which is actually true corrected and by gamma dot W. So, that way you get to see which is a corrected one basically with that you will be able to measure the corrected viscosity of it. So, there is another part of it which is called Bagley correction as I mentioned it to you while the you know from the reservoir this is the reservoir and then it measures there is some angle actually whatever I showed you a rectangular sort actually there is a angle many a times it is 45 degree angle is mentioned in order to get rid of the vortex part of it. But still then once it comes from a large diameter to small diameter from the reservoir to the capillary there will be always a pressure loss pressure drop. So, this pressure drop has to be corrected properly otherwise we will not be able to calculate out actually exact viscosity of it.

So, there are two ways it affects if you have a capillary one is the entrance and another is the exit. Exit means you can understand it is a pressure suddenly the pressure is released pressure is released to atmospheric pressure. So, these two components has to be well taken care of either way you can have to add some additional length virtually or physically you have to correct it to the pressure drop. So, both way you can take care of the entrance and exit effect that is what is the Bagley correction means. So, unless it is a very long capillary L by D ratio say 100.

So, in that case compared to small effects which you have what is actually happening inside the capillary it is more important then you can neglect those entrance or exit effect. So, otherwise in a realistic which is in between L by D ratio the entrance pressure drop is considerable and that viscosity data needs correction in that essence. So, entrance effects are caused by sudden changes of the velocity problem as I mentioned it to you from the reservoir I mean fluid as it extrudes from the large diameter reservoir through the much smaller capillary die we call it many a time capillary die. So, it is basically you can for the you can understand this diameter and this diameter is much different basically. So, the total applied pressure to the piston can be much greater than the actual pressure drop across the length of the die and if left uncorrected entrance effect cause elevated shear stress calculation.

You are getting overestimating that shear stress that you are calculating that needs to be taken care of. So, how to calculate I mean some of the things you know apparent shear rate is 4 q by pi r q a plot by del p versus L by r at constant you know and then finally, you have to calculate end effects let me show you graphically then it will be easier for you to anticipate. So, what we have done here see we have varied by L by D ratio, but kept the diameter constant of different at least 3 different types of capillary we have chosen 1, 2, 3 namely. Then we try to estimate del p versus L by r and then the line we got is straight line we extra I mean interpolate it and the x is this you know L by r you have you know got it you have to taken care of that particular correction factor. So, both way you can do either you take this extra length or else you have to take care of this pressure the y axis.

So, that way you can take care of entrance and exit correction. So, that is what if I put it in the equation see this extra e is added up here and e you get it from the you know where it intercepts the x axis the extra length part L by r part of it. So, the equation is 2 into L by r plus that that part is added up delta p is there. So, you can do either way as I mentioned either delta p whatever you have a delta p and correct it here or else the pressure part you correct it here minus whatever intercept delta p1 you got it and you leave it behind this.

So, that way actually you take care of. So, in fact and indeed if you just try to see from the plot see at the entrance you have certain you know pressure drop and at the exit also you have a additional pressure drop on top of that what is happening inside the capillary inside the capillary also there will be pressure drop. So, total pressure drop in addition to that pressure drop that happens within the capillary while so you have additional effect at the top when it is entering the capillary and when it exists. So, exactly that is what it happen and this exemplifies say Newtonian flow of HDPE or PP it is fine it is pretty much it has a elongation also involve here, but what if the fluid with pronounced non-Newtonian behaviour then you can see this additional vortex and that has a dead spots basically it spends little more time those particular part of the fluids and it actually exemplifies. So, practically this capillary length is there to there and if I really do that because of the entrance effect I have a additional passage here. So, this is the extra length and it boils down to Lm, Lm is Lc plus that correction factor.

So, this is what and ultimately doing the correction factor you actually end up having a too shear stress. I was overestimating. So, it is underestimated now because denominator that factor is added on hope it makes sense. So, two corrections I talked about one was with the Rabinowitsch's equation for non-Newtonian fluids what is the correction factor we have to add on and second thing is entrance and exit correction. So, ultimately this is the too shear stress above calculated too shear rate, too shear rate you get it from Rabinowitsch's equation and so if you take the ratio now you get the corrected viscosity.

So, another parameter is also equally important while processing your capillary data. So, that correction also you have to do is a wall slip. We consider while flow through a tube no slip condition actually it does not happen ideally there will be slip. So, because of the slip many thing happens say for example, it affects the product quality. So, if you consider no slip extrusion of polyethylene say for example, how smooth surface you get it.

However, in certain cases like say in a polyethylene case only, but with the surface you have a stick slip, stick slip so oscillating term. So, as a result you see grossly a rough surface generated. So, you did everything perfect, but only thing is that with the surface there is a wall slip phenomena going on. So, that is a so it was analyzed very early in 1931 by Mooney and the wall slip is a decrease in wall shear rate. So, ultimately what will happen wall shear rate whatever you are getting because of the wall slip there will be decrease the wall shear rate.

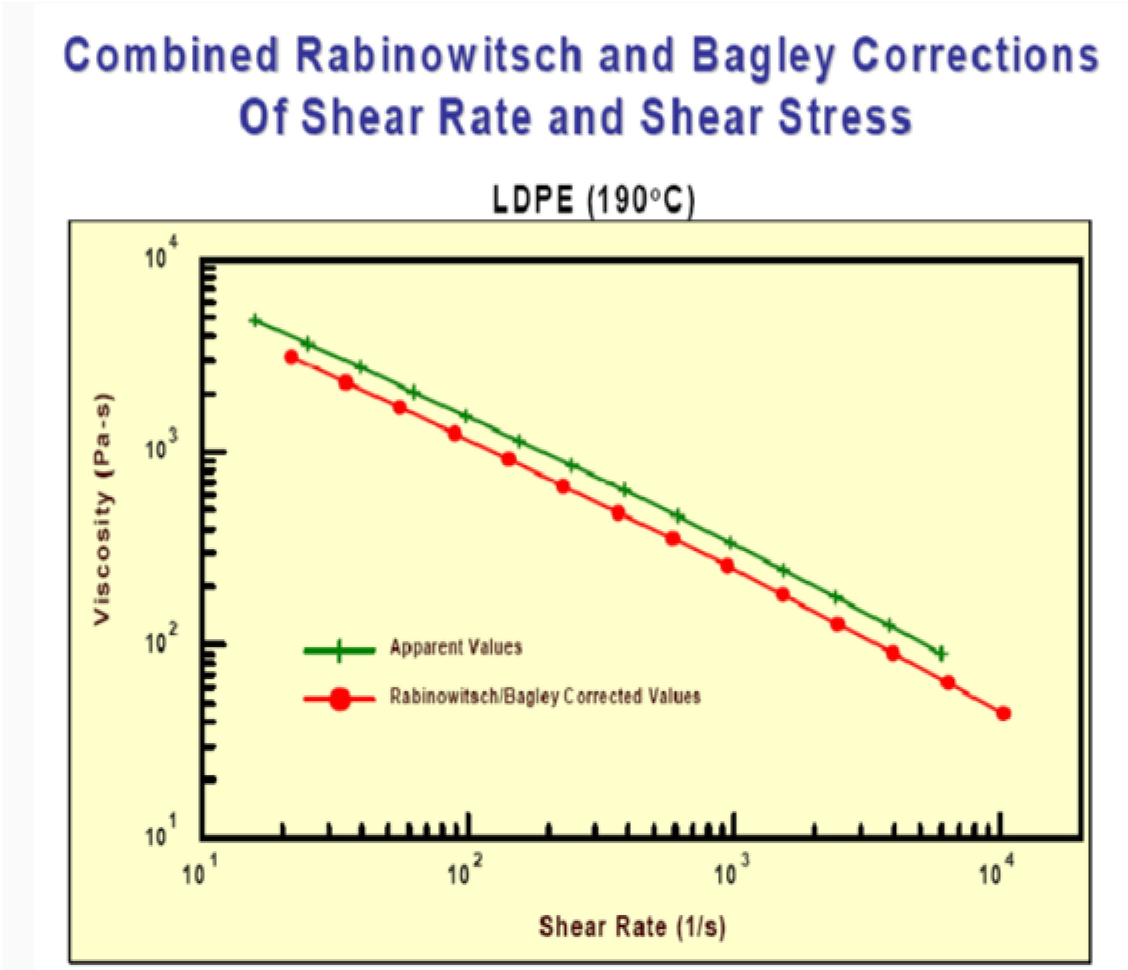
So, that is exactly what it happens I mean if it slips the velocity gradient is going to be less essentially. So, the assumption of no slip boundary condition is prominent in feed mechanics. Many a times we do we try to put that boundary condition invoke that boundary condition that there is no slip, but actually in real situation it slips. So, it is shown that rheological data uncorrected for slip can contain errors in shear rates as large as 70 to 80 percent, but significant actually when realistically it happen and spatially it will be it may be more pronounced at high shear rate. So, a migration of large diameter particles with the higher effective viscosity toward the center of the capillary increases the concentration of lower viscosity particles near the wall.

And the lower viscosity at the wall results in a greater change in the viscosity over the region and this phenomena is known as wall slip that is how you define wall slip basically hope you have understood the essence of it. So, it is reported that 1 millimeter of the product slip past the piston back to the capillary reservoir can cause 30 percent decrease in wall shear rate. So, that is what is it happens. So, wall slip during extrusion changes the physical appearance of the extruded as you can see from here.

Without the presence of slip extruded appear smooth. So, that is very very very important I will take it to the context when I talk about say extrusion of butyl rubber why you use EPDM. I will come to that context. Without the presence of slip extruded appears to be smooth and stick slip is caused by the extrusion of a non homogeneous mixture. It is quite quite quite common there. So, actually I am not going into the details of it, but because of this the average velocity changes.

So, what happens the velocity average and velocity average because of the slip. So, if you take these two into consideration you can calculate the corrected slip, slip corrected thing. If you just try to write down the equation 4 Vz average by R minus 4 Vz slip. So, slip velocity you have to calculate into 1 by R, R is the radius of course.

This the shear rate that is corrected because of the slip. So, obviously if you plot this 4 Vz by R which is the realistic quantity versus 1 by R from the intercept you can get the slip correction. In fact and indeed what it is being done you have to do an experiment with variegated diameter of that capillary and with same L by D ratio which I have to do the experiment to just capture this. And this is what the Mooney correction. I am not going into the details and by which because it is very difficult to get all this realistic parameters measured rather than that you try to do it graphically. As I mentioned it to you while you are correcting the entrance and exit effects specifically.




In a similar way you can do in a graphical method by conducting the experiment with different diameter of the capillary with same L by D ratio because in this case we are not going to consider the entrance and exit part of it and you can pretty well correct it for the slip, wall slip phenomena. And exactly as last time I depicted that because of the slip what happens the flow actually gets you know it changes basically. So, in combination if you do Rabinowitsch correction, Bagley correction and of course the wall slip if you take it into consideration. So, the realistic data which you get it from apparent values apparent stress, apparent shear rate dividing that the viscosity you get it that changes the blue one represents the uncorrected one and red one represents the corrected one. So, you can see what is the rate as I mentioned 10 to 10 to the 4 second inverse range you get that data now.

**Weissenberg-Rabinowitsch correction**

$$\dot{\gamma}_W = \frac{4Q}{\pi R^3}\frac{3n+1}{4n}$$

$$\frac{d\ln Q}{d\ln\tau_W} = \frac{1}{n}$$

And these data you can ultimately combine with you know rotational viscometric data. So, you have even more extended you know master curve of course you apply Cox-Merz principle I mean provided that it is valid up to that shear rate region otherwise it is not valid as I mentioned if you do it really the parallel petriomic measurement at a very high shear rates there may be some edge effects that may contribute. So, up to that you have to consider and then try to overlay and try to see how rheologically you have to it is viscosity versus shear rate and feed it into the parabage model and you know that how your particular system is going to behave like. So, this is Rabinowitsch correction and with that correction you get this data basically for a parabola fluid say for example. So, the Rabinowitsch correction will result in higher shear rates especially in the area of higher shear thinning sort of a behaviour.

So, there one more thing is left both in rotational, rotational as I mentioned you directly can measure the first normal force difference at least second you can calculate out. So, this first normal force difference amounts to the dice well or calendar shrinkage. The second normal force difference is related to the surface roughness in the z direction basically how the surface looks like. So, these two are very very important the first normal force difference how it is reflected rod climbing effect as I mentioned it you just rotate have a rotor a stirrer rotate on a concentrated polymer solution or polymer solution or even a polymer melt there will be rod climbing effect. And same is the thing it happen when you extrude a polymer it may be plastic, it may be a fibre, it may be rubber you see the swelling in terms of diameter once it comes out of the you know die.

So, those are because of the elastic instabilities in general it is called and that is because of tau xx minus tau yy that is the first normal force difference. So, for a Newtonian fluid it is 0. So, when water actually comes out of a pipe normally you do not see if it is a slowly done you do not see the other effects I mean if you get rid of. So, then you do not see any changes in diameter, but which is do see the changes on diameter in any any macromolecules because of this fact. When a an elastic polymer solution and melt is forced to flow it is less compressed in the direction of the flow than in the two other normal direction.

So, that is what it is very important to this is the die swell you can see this is swollen compared to the you know diameter of the capillary essentially during a while extruding. So, die swell versus die length if you plot it. So, you can see with the die length basically it changes if you increase the die length the die swell phenomena will significantly you know die down basically. It happens because of the fact when it elastomer comes through it gets elongated. If you have a long capillary die it relaxes basically and that relaxation actually will happen within the capillary.

So, that while extruding out coming to the atmospheric pressure or it does not really swell in the other direction that much. So, that is how you can anticipate that with just playing with the normal force differences you can you can changes the die swell because if you have a die swell specially if you have a corrugated profile wherever there is a stress concentration and that is going to be swelling more. So, compared to the die it will be more deform or safe you are going to get I will talk about it later. So, that is what tau xz in perpendicular to the tau yy.

$$N_1 = \tau_{xx} - \tau_{yy}$$

So, tau xz minus tau yy is the first normal force difference. Now, the second normal force difference is other one tau yy minus tau zz that reflects on the surface of it. So, separate attempts have been made to predict the extruded swell numerically through the equations relating the swell ratio d by d I mean of course, d is the extruded diameter by diameter of the die and to force normal stress differences in 1 W and based on the theory you can this is the theory and where it is directly proportional to wall shear rate shear stress and of course, d by d. So, that way you can calculate it out and there are several theories a with in which you can calculate through the capillary die. So, you have to calculate maximum shear strain and also the shear rate from there also you can calculate basically in capillary way. So, I am not going into the details, but this is what it happens, but calculating non second normal force difference is little tricky.

➢ **The Second Normal Stress Difference is**

$$N_2 = \tau_{yy} - \tau_{zz}$$

$$N_{1w} = 2\sqrt{2}\tau_w\left[\left(\frac{d}{D} - 0.13\right)^6 - 1\right]^{1/2}$$

So, physically show you if you just try to consider a droplet a nutrient fluid and actually vice versa you try to see a non nutrient fluid free front and side view see is a tapered and that reflects in the surface roughness as a whole when you extrude basically. So, we are not going into the details we will try to see as on when required, but nonetheless I would like to get you familiar with the N 1 and N 2 namely first normal force difference second normal force difference. First normal force difference is directly related to dice well calendar shrinkage, Weisenbauer effect whereas, N 2 is related to the surface roughness of the extruded or finished profile that you get it N 2 is negative and the order of 20 percent of N 1 for the most common polymers. So, anyway if time permits in the purview we will try to show you how you can estimate the second normal force difference as well the first normal force difference precisely from the capillary geometer. Then parallel plate geometer from the bearing itself whatever lift up force it arises that is proportional to N 1 that you can directly measure it physically essentially.

So, these are the some of the references as I have given you already I am not depicting, but most importantly what I talked about here is the capillary geometer advantages disadvantage. Disadvantage is this that it does not give you the exact shear stress or shear rate it is a gross average value get it compared to the parallel plate geometer advantages. Disadvantage is done and then shear stress shear rate how to calculate how to correct it using the avenues correction for the shear rate for the back lay correction for the shear stress wall shear stress for example. And of course, so the money slip condition how to get rid of the correction for the slip and finally, we talked about two normal force differences one is the first which is directly related to die swell or calendar shrinkage and second one is the normal stress differences which is related second normal force difference which is related to the surface roughness that you get it surface topography. So, up to that pretty much covers the re-homometry in the next class on we will try to go the one by one by different classes of polymer first we will start with the paints then we will go to the plastics fibers and then rubbers and then we will come back to the how to apply it basically in the processing front.

So, you get you familiarize the processing with the demonstration with the numerical calculation and then we will go for the CFD part of it. So, next coming up lecture is introduction to paints and its importance to rheology in paints basically what is significance. Till that time please stay tuned. Thank you.