Rheology and Processing of Paints, Plastic and Elastomer based Composites

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Lecture 04

Classification of Fluids

Welcome to NPTEL online certification courses on Rheology and processing of paints, plastic and elastomer-based composites. Today we are in week 1 and lecture number 4 and we will try to do the classification of fluids here. Try to see. And then the concepts essentially covered will be real and ideal fluids. I mean ideal fluid means as I mentioned it to you like a Newtonian fluid say. Then Bingham plastic fluid, then power law equation, pseudoplastic fluids, dilatant fluid and we will go to the two different types of time-dependent fluids namely thixotropic and rheopectic fluids.

Once again keywords as I mentioned why the keyword is kept specifically. I mean after this lecture you may read. While reading you may search some of the basic scientific. So, fluids again as I mentioned it to you, you can have fluid and that is actually a ideal fluid.

And the real fluid and then the Bingham plastic is a special type of a fluid. I will mention how it behaves. So, real fluid again I mean although Newtonian can be considered as close to ideal fluid but still not ideal. Let me clarify at this stage. And then you have a non-Newtonian fluid which does not obey the Newton's law of viscosity as I mentioned in the other classes.

And then this non-Newtonian fluid is further categorized into time independent and time dependent fluids. In the time independent class you have mostly two major types of fluids here and in that you have a pseudo plastic and dilatant although there are other varieties also but I am not going into that complication at this stage. So, you have pseudoplastic and dilatant type of fluid which most of the majority of the polymer or filled polymer system suspension system that behaves. Another special class of fluid which is time dependent and dependent in the sense that viscosity at a given shear rate changes as a function of time. So, they can be again depending on their trend whether it is over time increases or decreases you can further classify into thixotropic or rheopectic.

So, that is a whole classification of the fluids that exists. Once again when I talk about a polymer it can be in the form of a molten stage, it can be in the form of a solution stage, it can be even when I talk about the paints and all it can be even a suspension say. So, it is having many other things including say pigments other process aids along with the base polymer resin that is the composition of a pen in a nutshell say. So, that is what it is. So, now let us try to look little bit into that.

Whereas fluid viscosity should be 0 that is the ideal case. So, no resistance to flow it should perpetually flow that is the ideal case. And that fluid should be incompressible infinite bulk modulus if it is incompressible so you can understand k the bulk modulus with the pressure the volume change shouldbe I mean minimal that way. And this exists in theory, but it is a kind of a no slip boundary conditions is applicable. See when I talk about a fluid flowing through a pipe or flowing through a channel I will cover in the next subsequent upcoming classes.

So, if you just consider it is a stack of cards stack of fluids one fluid layer another fluid layer starting from the boundary layer with the conduit surface. So, you imagine the friction in between those layers as 0. So, classically you can say that is a mu equals to 0 and energy loss therefore it is 0. So, if you consider a fluid flowing through in between a pipe it is a pipe, but in a two dimension you can see it like a in 2D representation of it. And in the linear way in one dimensional you see that is flowing from say this point A to point B is flowing.

Friction = 0

$\mu = 0$

Energy Loss = 0

So, if you look it at the profile since there is no viscosity in between whatever pressure you have because of that it is flowing the complete layers and they will flow it flow at a equal velocity each layer. On the contrary if you take the loop into the real fluid where the viscosity is not 0. So, viscosity not 0 means in between the layers in between the stack of cards you have a friction. So, as a result starting from the beginning point to the end point if you look it at with the metal surface or whatever surface you have of the conduit the where fluid is flowing you have a friction. So, it cannot flow that much.

Friction ≠ 0

$\mu \neq 0$

Energy Loss ≠ 0

Next layer has a little bit more I mean less friction, but still friction and at the middle point of it it has minimum friction. So, that way you can have a parabolic flow line. So, it is the case for the real fluid and to be very specific it is a case for the Newtonian fluid say for example. So, here the fluid is compressible having finite bulk modulus exists in nature ideal one it is theory only like your ideal gas no gas is ideal. So, like likewise no fluid is ideal fluid technically.

So, try to imagine if the fluid would have flow without any resistance how much energy could be saved. So, there is also another point of view that you can think of. So, no slip boundary conditions are applicable. So, here no slip boundary condition no slip with the you know the body of the metal surface or something. So, if it is so the friction is not equal to 0 between the layers so is a viscosity and so is the energy loss.

So, while making that fluid thrown from again A to B you have certain amount of energy dissipation energy will be lost in the from the system whatever energy you are providing that way. So, that is the classically the difference between the ideal and real fluid. So, another class if you recall I talked about a Bingham body. Bingham body is again it is a real body, but again it is not the ideal one it is not most I mean you see what it is see if you plot shear stress with the shear rate. So, you will find for a Newtonian fluid I will come back again Newtonian fluid I talked about where you know if you plot shear stress with the shear rate it actually goes hence and hence and the slope of it is nothing but the viscosity.

So, that is the Newtonian fluid. So, Newtonian fluid flows it will get it from the origin it is a straight line behavior. On the contrary if you have a Bingham body you need to apply certain force only certain stress only up to that it will not flow and after that it will flow and that is what is called in stress or tau y So, you see this Bingham body which still obeys after that the Newton's law you see that is increasing. So, it can be Bingham body on top of that it can be viscoplastic like it can show you another behavior like shear rate dependent viscosity it is not the Newtonian type. It can be I mean same vene type of fluid that means it stays something like a parallel and it can be like that only also.

So, this is a sub classification I mean sub class of a fluid which actually flows but it will flow after giving some in stress value. So, that is what is I mean Bingham fluid. So, classically Bingham plastic fluid requires a certain force to develop the in stress and before after that it will start flowing like a classically Newtonian fluids only. So, there are certain real life examples your toothpaste for example as I was mentioning other day you put some force only that you then only that your paste will come out of the nozzle. So, similarly the mayonnaise and chocolate.

So, what it happens viscosity of the fluid is constant during the flow at shear stress higher than the stress. So, more or less after that it is a Newtonian fluid in this case if I just the rate track of the rate line if I follow but of course there is another sub classification of which is visco plastic that means it will change with the shear rate basically. So, it increases simply as stress approaches is ill stress and the rest they developed a 3D structure due to the intermolecular and inter particle forces. So, that has to be broken now then only it will start flowing and this structure resists the deformation till the applied force give enough energy. So, it actually its structure so develops that it will not allow it at the first place to flow.

So, its sufficient force if you break apart that particular structure then only you are ready to be flown that is what is a basic says. So, once the fluid begins to flow then it is not a problem it will flow as is and visco plastic fluid again the blue line whatever is drawn here it is they so in stress but during the flow do not flow like a Newton's flow. So, they have a in stress then after that it is not a Newtonian fluid and whatever fluid is I am coming there. So, it is following pseudo plasticity. Now, let us try to see I mean I was uttering many types of fluid and then you see those are all non Newtonian fluids.

Again if I plot shear stress with the shear rate you see the Newtonian fluid and if you plot in terms of viscosity which is nothing but the ratio of shear stress divided by shear rate that means eta or mu see do not get confused because sometimes we are writing mu sometimes we are eta is nothing but here by gamma dot. So, this is your viscosity. So, if I plot viscosity with the shear rate the Newtonian fluid stays constant across the shear rate you apply. While the pseudo plastic is shear thinning type with applied shear rate if you increase its viscosity is going to go down. While for the dilatant fluid it is going to go up it is just opposite to that behavior.

So, again coming back to the shear stress versus shear rate plot Bingham's stage here your pseudo here your pseudo plasticity shows like this sort of a behavior like. So, you can understand now in the Bingham if I superimpose this behavior like I was talking about there the visco plastic fluid is called visco plastic behavior. So, there you have this reflection of pseudo plasticity, but you have a in stress that has to be applied to make them flow. So, actually this is called pseudo plastic again you please remember pseudo plastic means shear thinning dilatant means shear thickening. So, classic example of pseudo plasticity is a quicksand.

I mean if you the person stands there fine it is a kind of a Bingham type of a response visco plasticity. Then the person starts moving the viscosity reduces person goes inside there. So, that is how it happens I mean it is typical shear thinning sort of a behavior. So, you have up to this about the non Newtonian fluid time independent again I will say you got the point it is of at least dilatant is a special type of a fluid keeping it aside at least other than Newtonian you have two types of responses. These are Newtonian you have either shear thinning or shear thickening type behavior.

Now, the pseudo plasticity means shear thinning, but in actual case pseudo plasticity means at a very small shear rate and at a very high applied shear rate in ideal case I am talking about it is not a exactly the Newtonian sort of a behavior in between I mean in the two extreme terminals you have a Newtonian behavior in between you have a shear thinning type of a behavior. So, that's what the first Newtonian region sometimes called upper and lower Newtonian. So, low shear rate region a small range you have a Newtonian behavior the slope is 1. And then in between slope is less than 1. So, in between C and D you can see it as a behavior of a pseudo plastic or shear thinning behavior.

And again at very extreme high shear rate you have again once again slope is different. So, this is a very ideal sort of a behavior that normally I mean is exhibited by real polymer solutions many a cases. So, this is a typical plot even in some of the fluids which is not non-polymeric in nature, but you we take it in every day as a food material say tomato ketchup say whipped cream I mean you use it for cake making. Those are all the rheologically they behaves just like that if you plot shear stress with the shear rate you have a lower Newtonian behavior or a upper Newtonian behavior in between the pseudo plasticity. So, we will come back again there, but this is the case.

So, now how to describe the pseudo plasticity that was the first challenge. One of this model or theories or equation is called Oswald de Waele equation. It describes if I plot shear stress and with the shear rate it follows tau equals to k which is a constant into gamma dot to the power n. So, if you just in a modified form also you can write gamma dot equals to some other constant I mean into tau to the power nu also that is how it is also represented. So, nonetheless if I consider the first equation if it is equation number 1 this is the modified one only.

$$\tau = K\,(\dot{\gamma})^{n}$$

This k and n are the constants power law constants. Well for v if I just represent it different way like tau dot equals to a into tau to the power nu and in that tau equals to exactly 1 by n and which is a power index basically and A equals to 1 by k to the power 1 by n. So, if I take a logarithm of it the first equation you can see log tau equals to log k into n into log tau dot. So, obviously if you just plot log tau versus log tau dot from the intercept you get the value of k and from the slope of it the n can be calculated estimated. So, you do the real experiment with tau versus gamma dot and you have a log log plot and from that very easily if you try to fit it in a power law equation or Oswald De Waele equation you can easily calculate the k and n values which are the constants.

$$\dot{\gamma} = A\,(\tau)^{v}$$

K and n are power law constant

where, $v = 1/n$ and $A = \left(\frac{1}{K}\right)^{1/n}$

$$\log \tau = \log K + n \log \dot{\gamma}$$

relationship between μ_a , K and n

$$\mu_a = \tau / \dot{\gamma}\ ;\ \tau = K\,(\dot{\gamma})^{n}$$

$$\mu_a = K\,(\dot{\gamma})^{n-1}$$

So, often we denote a apparent viscosity from here although it is a power. So, if I just simply take as I mentioned tau by gamma dot is called viscosity as I mentioned if you consider the Newton's law of viscosity where it was exactly proportional and then this mu is called mu apparent or eta apparent and this is what is called apparent viscosity. Many a times apparent viscosity is used. We will come over there especially when we will try to cover the capillary geometry. That time we will be covering what is apparent what is the significance of it and how do you have a corrected viscosity for example, after certain corrections.

So, considering again mismatch of conception you know eta to sometimes mu eta and mu are invariably actually same So, you can simplify this equation and then you can have that way apparent viscosity. So, considering eta r as the apparent viscosity at some arbitrary reference shear rate of course, specific to a particular shear rate and then you can calculate eta by eta r equal to gamma dot by gamma dot to the power n minus 1. So, that is how it reduces and if you just consider eta equals to 1 second inverse then your equation falls down to eta equals to eta 1 into gamma dot to the power I mean eta 1 is nothing but the at 1 second inverse what is the viscosity of it. So, that way you can transform from 1 shear rate to the other very easily. If you know at a shear rate of 1 second inverse what is the viscosity you can calculate out that at other shear rate what can be the viscosity that way and that is what I was talking about.

$$\eta / \eta_r = |\dot{\gamma} / \dot{\gamma}_r|^{n-1}$$

$$\eta = \eta_1 \ |\dot{\gamma}|^{n-1}$$

You can always have a log-log plot and then I mean you see it is a typical the A is a dilatant material but obeying the power law and then a Newtonian material the B C is a pseudo plastic material and D is a typical polymer when it is a pseudo plastic but which does not overlap the power law. So, that way based on this exponent value you can have a different types of responses and exactly when I will touch upon the geometry then what you have to do ultimately you get the data, data is nothing but your shear stress versus shear rate. So, you have a log-log plot and try to calculate out the slope of it and depending on the response like I showed you systematically A B C D you figure out exactly where it is matching and then next step will be try to fit in with a appropriate fluid model and then you go for from there. So, we will go step by step. So, once again to repeat A is a typical dilatant material you can see very clearly it has a stress and then which obeys a power law whereas, the second I mean B C and D cases there are typical a Newtonian fluid and some point of time here and then rest are all pseudo plasticity but these two pseudo plasticity is little different.

So, anyway we will touch upon as on when it will be I mean applicable. So, again dilated fluid material shows an increase in apparent viscosity with increasing shear rate that is the dilatancy of it shear thickening. They exhibit constant viscosity at low shear rate again is a lower part of it is kind of a Newtonian response. Like I mentioned for pseudo plasticity if I go back see what I talked about is this two terminal is more or less like a Newtonian things but in between you have a typical power law equation which is actually or that equation is valid there. So, increasing with the viscosity increasing shear rate in the intermediate region and again once again like similarly at the high shear region the behavior is not well established due to the shear thickening effect.

Here the second terminal is not very well I mean not goes exactly what I talked about for the pseudo plastic cases. So, actually they are not very common but it happens with a highly filled system. Highly filled polymer propellant system like hydroxy terminated poly butane for rocket propulsion the high energy material that discuss this kind of a behavior typically PVC plastic So what happens actually with the shear rate if you have asymmetric filler or suspension system that actually I mean gain some sort of a you know orientation there and that is why the viscosity increases it resist that particular structure resist the flow and that happens with the increasing shear rate . So, this is a typical of plot of it you see you know this is the Newtonian although it is shown here Newtonian but sometimes it is you do not see it for this specific case.

But in between you get a different response. See this is what it is shown schematically here. See pseudo plastic the first one with the shear rate apparent shear rate flow becomes eased out. While in the other case for the dilatant case because of the structure formation this is oriented structure formation as you increase the shear rate it is going to resist the flow. So, it is called shear thickening phenomena.

Quickly look into the time dependent rates. Viscosity is expressed as a function of shear stress shear rate and time as I mentioned it to while talking about the constitutive equations. So, viscosity is going to function not only shear stress shear rate also time as such. So, this is a classical example you see if I plot viscosity with the time at a constant shear rate of course. So, you get to see for a thixotropy viscosity reduces. Geopectic other way round like I mentioned it for you know pseudo plasticity and dilatancy in a same line.

But it is a time here x axis is a time function. So, in fact if you do the you know experiment such a way from the low shear rate you increase and you try to come down. So, you end up having hysteresis loop and this is the hysteresis loop generated for this thixotropic material. Here the plot is shear stress versus shear rate other way round. And then it is the rheopectic behavior. So, you end up having the hysteresis of it and that is actually indirectly measures the energy lost from the system like any hysteresis experiment you do it.

So, thixotropic is a property of a body where the apparent viscosity temporarily reduces by you know previous deformation. Example see it is happening because of the it has a implication of the previous you know deformation at a lower shear rate and that is getting accumulated. And it happens for the paint, ink, blood castor oil, and adhesive paste. The viscosity depends on the time of stirring as compared to the pseudo plastic material time was not a factor there that is why it is called time independent fluids. The thixotropic behavior can be demonstrated using rotary viscometer.

We will touch upon when we will talk about the viscometry say. The loop shown is the characteristic thixotropic loop and the size of the loop will depend on the time for which the material is sheared at each speed and maximum shear rate used and flow characteristics of the material. But of course, there is another interesting material characteristics which is called anti thixotropy. What is that? Anti thixotropy is when apparent viscosity is an increasing function of duration of flow and the body recovers its initial state after a long rest time. So, this is the typical special behavior called anti thixotropy.

rheopectic is exactly I mean in opposed to you know thixotropic. Here over time the viscosity increases. Typical example gypsum paste and printer rings. So, increase rate of solidification is observed upon gentle movements and pseudo plastic fluids are dilatant type, but with time dependence. Earlier one thixotropy was like pseudo plastic type, but time dependence.

In this case dilated type with time dependence. And the fluid when deform first with increasing shear rate shear stress and then with the decreasing do not flow the same path back and that is how you generate the hysteresis loop. And the area under the hysteresis loop shows the loss of energy as I mentioned its cycle of flow. The same as I mentioned in solidus behavior it is a liquidus behavior we were talking about. If you do you know static mechanical experiment you stretch the sample bring back. The same viscometric experiment that your material is in the fluid state.

So, it is same to same. And the energy is consumed due to the changes in molecular configuration and other structural changes as a result of shearing. So, definitely as I mentioned it you because of shearing you have a structure build up there. So, that is it about the fluids and some of the books we have added two more books here to go into the rheology fundamental fluid fundamentals. These two books are Malkin books by rheology of polymers, but second book I like it I mean I started reading rheology from this book when I was a student actually.

This book was by Carreau. And in fact you will be surprised to know there are certain fluids which are named after Carreau that is also we are going to cover. So, quickly to conclude I talked about a real fluid and ideal fluid real I mean ideal fluid is actually is not possible. Then Bingham plastic fluid which is also a special types of a fluid which actually develops its flow after yield stress. Then I defined pseudo plastic that means shear thinning type and dilatant shear thickening type. And then in the same line we talked about time dependency over which like the what time the viscosity decreases same as like maintaining the pseudo plastic type of order you call it thixotropic fluid.

And if it is other way round what time the viscosity increases like thickening type or dilatant type you call it rheopectic type of fluid. So, up to this is fine now we will try to what we are going to do taking those fluids or some special types of a fluid model we will try to see or demonstrate how it flows because ultimately what I told you it is linked to the flow linked to the manufacture. So, that essentially you will be enjoying in the next upcoming classes up to that. Thank you very much.