Fundamentals of Food Process Engineering
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Lecture – 05
Food Rheology (Contd.)

Hello everyone. Welcome to the NPTEL online certification course on Fundamentals of Food Process Engineering. Today we will continue with the topic Food Rheology, that in the last few classes we were discussing about. So, we have discussed about the fluid food in the last class. Fluid food in the sense what are the different kind of fluid food and what are the different models that we can use for them. We know that basically we can divide them into Newtonian and non Newtonian fluid, and the again another category is time dependent fluid flow behavior. So, there are different model we have learnt it in the last class.

Now, today we will see that there are few application of those kind of food rheology in the industry, ok. So, this is very important to know because when you deal with the different food processing industry, then rheology has an important role in designing the various equipments used for processing, ok, and so, therefore, we will discuss it here.

So, today's discussion is based on mostly the application of rheology in the fluid food processing.

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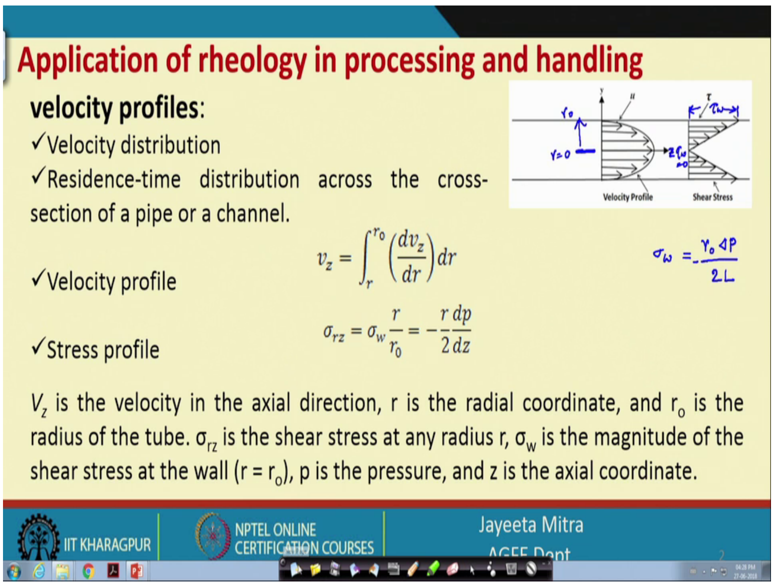

So, we will discuss the application of rheology in processing and handling. The first thing if you go to any fluid food processing industry, so, there are many pumping system and tubing system you need to design through which you are fluid food is moving, ok.

So, what happened that in our momentum transport classes, some of you might have done that, so, momentum transfer classes we have learnt the different relation of you know pressure drop and the flow velocity inside a pipe, right. So, that is basically Hagen Poiseuilles equation. So, those equation when we deal with the velocity profile, velocity profile depends on type of fluid, ok, and also the pattern of flow, that is whether it is laminar flow or turbulent flow ok.

So, in this application section we will we will couple the, those equations with the rheological equation or rheological modeling of the fluid food. And that will help us to understand basically the velocity distribution in case of a pipe flow or if you want to see the residence time distribution in a in a processing vessel, ok.

So, first we will see this one velocity distribution. We know that in general case, if you consider this as a pipe, ok. So, this is a pipe, a cross section we have taken, and we are considering a steady state condition of flow of Newtonian fluid in a laminar flow. So, then we can get this kind of a parabolic profile, this is the velocity profile, if we can consider this is as the center point.

So this is R equal to 0 and this is the inner boundary that is r o that is the maximum radial distance for the wall. And here the stress profile also we can see, so, stress will be maximum at the wall that is tau w, and stress will be tau w this is equal to 0, ok, let us see this is the z direction, this is r direction. So, this is the velocity profile and shear stress profile inside a pipe flow for laminar steady flow condition.

Now, when we deal with some different kind of fluid, then what will be the velocity profile, and what will be the stress profile? That will help us to design those systems,. So, these 2 things we can learn from that, now in general velocity profile if you want to express we can write this equation that v z, ok, velocity in the z direction will be equal to integration r to r 0 divided by d r into d r ok.

So, the general representation of the velocity in the z direction. Similarly, stress will be sigma r z ok that is the stress because of the z directional flow in the r direction what will be the stress. So, that we want to measure, right, and that is equal to sigma w; that is, stress at the valve into r by r 0, because r 0 is at the valve whether stress is sigma w and r because sigma r z is at any r any radial distance right.

So, this is equal to minus r by 2 into dp by dz, ok. Because tau w the value of tau w or here the sigma w that is equal to r 0 into delta P by 2 L, ok, minus so, that is why r by r 0. So, r 0 gets cancelled, r minus r into dp by 2 into 2 z, whether L is replaced by d z considering a small distance in the z direction, ok. So, here v z is a velocity in the axial direction, r is the radial coordinate r 0 is the radius of the tube, sigma r z in the shear stress at any radius r as a mention, ok. And P is the pressure and z is the axial coordinate, ok, now from this we will see what else we can calculate.

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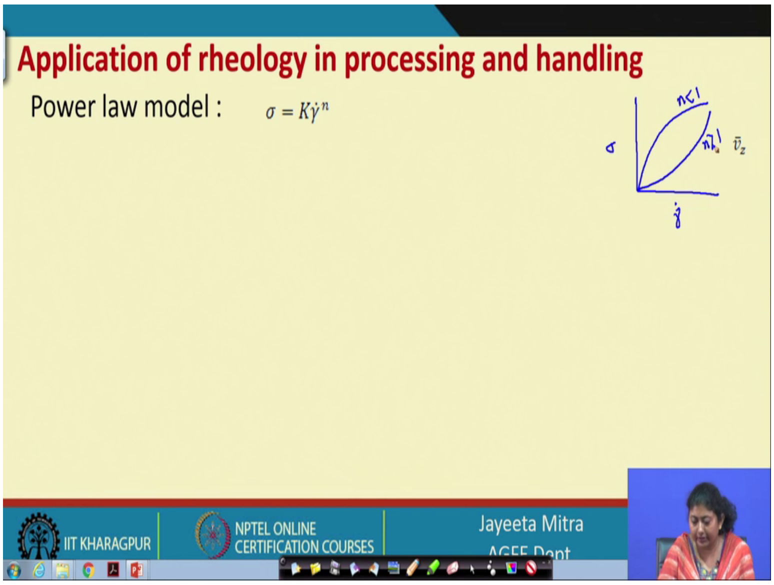

Let us now considered that instead of Newtonian fluid, we are taking a power law fluid, ok.

So, for the power law fluid we can model it like stress sigma that is equal to this is shear stress here, sigma that is equal to K into gamma dot to the power n, ok. So, consistency index K into sheer rate to the power flow behavior index. So, of course, the power law model we know that n is not equal to 1, if n becomes one this will become the Newtonian fluid.

So, power law model if you remember that in the fluid food rheology we have seen that the behavior in the in the shear stress verses shear diagram will be like this way, or this way right.

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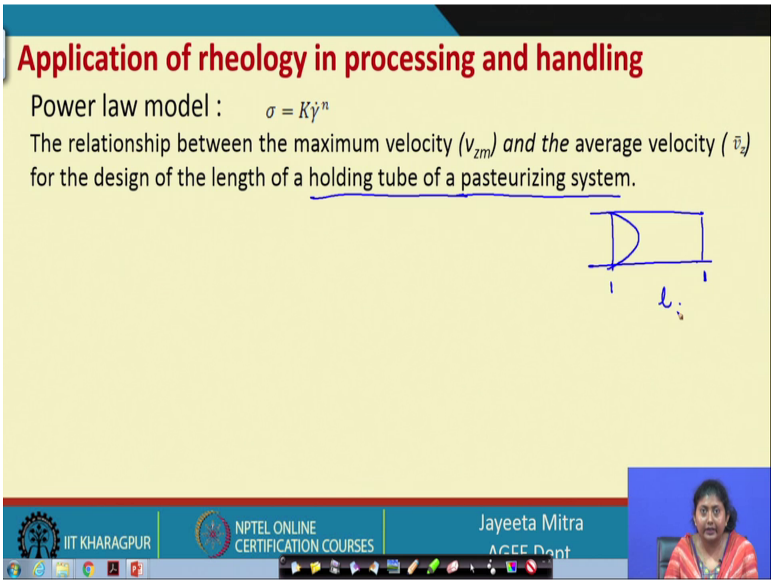

So, n less than 1 and n greater than 1 the relationship between the maximum velocity v zm and the average velocity v z bar, for the design of length of a holding tube of a pasteurizing system; this is where the interest lies now; that is, when you need to design the pasteurization system and basically the holding tube. So, the idea is we need to keep the fluid food in the holding tube for a certain length of time,.

So, if in the tube section, if your flow is the most common behavior if it is a parabolic flow, and then there is certain point to certain point there is a length of the holding tube, ok. So, your liquid food has to pass from this point to this point, and it should stay there for the required length of time. So, that the all the area the farthest area of the product can be heated, and that the target microorganism will be killed as the aim would be right.

So, we need to see that what is the time required for the fluid to come from this point one to point 2 or the or to cross the required length, right. For that we need to analyze the what is the average velocity, and what is the maximum velocity, right.

Because you maximum velocity point may reach there early, but the all other points in the tube may not reach to that extend with the short time and if any such thing happens that the whole fluid is not exposed to the required temperature for a for the required duration of time then the contamination may be there. So, for that we need to know the relation between the maximum velocity, and the average velocity for the particular kind of fluid, ok.

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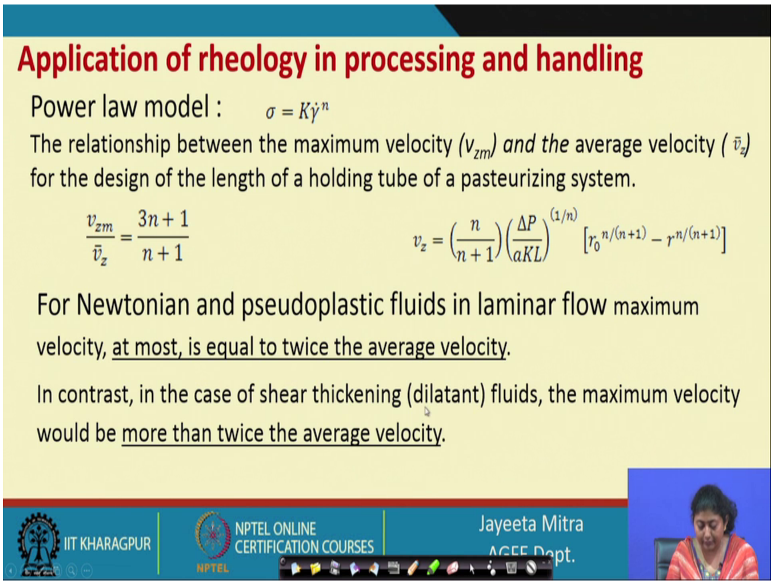

So, for non-Newtonian fluid z directional velocity can be simplified by this equation. Now how we have got that? In the initial equation of v z, we need to put the value of v z in terms of in terms of this equation, which relates with the you know the flow behavior index, ok.

So, this derivation is done in the momentum transfer. So, all of you who are taking that course or already have done that may know this thing, here we will just focus on the application, but you can get this in any unit operation on momentum transfer book for example, zincoplex zincoplex (Refer Time: 11:43) also you can get this. So, what is the important part here, that we have got the value of or the expression of velocity in terms of this n; where this n will differ for different food, ok, different fluid food, right.

So now, we can get this expression of v z, ok, and r 0 and r is known to us for any distance if you want to calculate the v z we can do that. And from this we can get also the expression of average velocity, ok, averaging over the whole cross sectional area and the maximum velocity. So, maximum will be at this center, so, maximum velocity we can calculate by calculating the v z at R equal to 0, R equal to 0. So, we can get the maximum one so, the ratio of maximum to the average is this one 3 n plus 1 by n plus 1 ok. So, if we know the value of n we can get the idea that in what ratio, this will vary and based on that we can decide then how long the product should be there in the holding tube or what will be the length of the holding tube.

Now, for the Newtonian and pseudo plastic fluids in laminar flow maximum velocity at most may be what if it is Newtonian n will be equal to 1. So, 4 by 2. So, twice the average velocity will be the maximum velocity, right? So, for the Newtonian and pseudo plastic; where n is less than 1 fluids in the laminar flow maximum velocity will be at most equal to twice the average velocity.

If it is pseudo plastic, it may be even less than that at most it will be there twice the average velocity; however, if we deal with dilatants fluid where n is greater than 1, ok. So, then the maximum velocity would be more than twice the average velocity, ok. Maximum velocity is more than twice the average velocity; that means, the fluid of the other part which is not in the maximum velocity area needs more time to cross the you know one point to the other,. So, that so, that length of the holding tube we need to design or other presidents time we need to provide in such a way so that all the fluid will be exposed to the proper temperature of the pasteurization. So, therefore, the understanding of rheology of different fluid food is very important.

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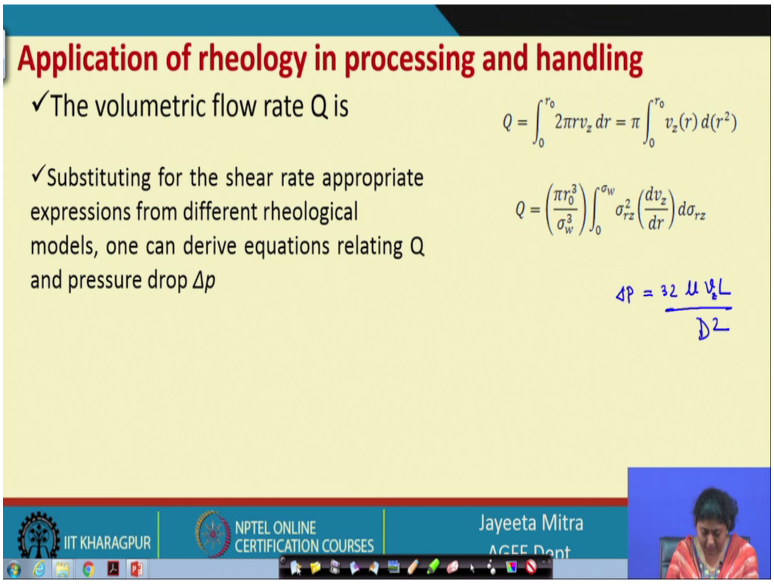

Next is if you want to analyze the volumetric flow rate. So, volumetric flow rate what we can do? Simply we can integrate from 0 R equal to 0 centered to r 0, 2 pi r d r into v z, ok, v z is the velocity. So, v z which is the function of r, ok, and here we can write d of r square. So, that pi is coming and 2 r we have taken in that way d of r square like that we can write. So, from this instead of expressing in terms of velocity, substituting for the shear rate, appropriate expressions from different rheological models one can derive the relation of Q and the pressure drop, ok.

So, Q which is the volumetric flow rate that relates the you know that that is equal to actually, volumetric flow rate is the area and the velocity, right? Velocity has a relation with the pressure drop that we can get from the Hagen Poiseuille equation, ok. Basically if we write that delta P that is equal to 30 2 mu v L by D square; where L is the length of the pipe, v is the velocity v z we can say mu is the viscocity or apparent viscocity or effective viscocity and d is the diameter of pipe.

From this we can relate, we can derive the equation relating to Q and the pressure drop. So, so here in this equation, what we have done that we have change the velocity to the shear stress expression. Shear stress and shear rate expression and thus we are relating the volumetric flow rate to the Q that is volumetric flow rate and the pressure.

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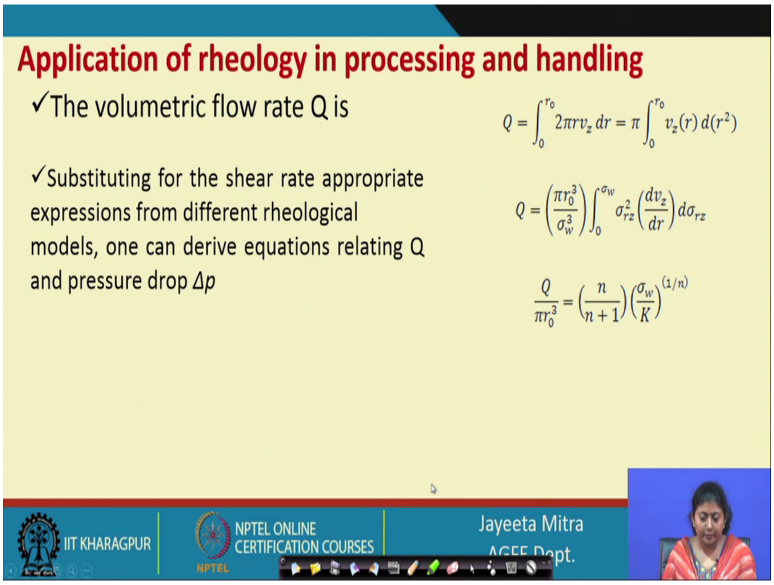

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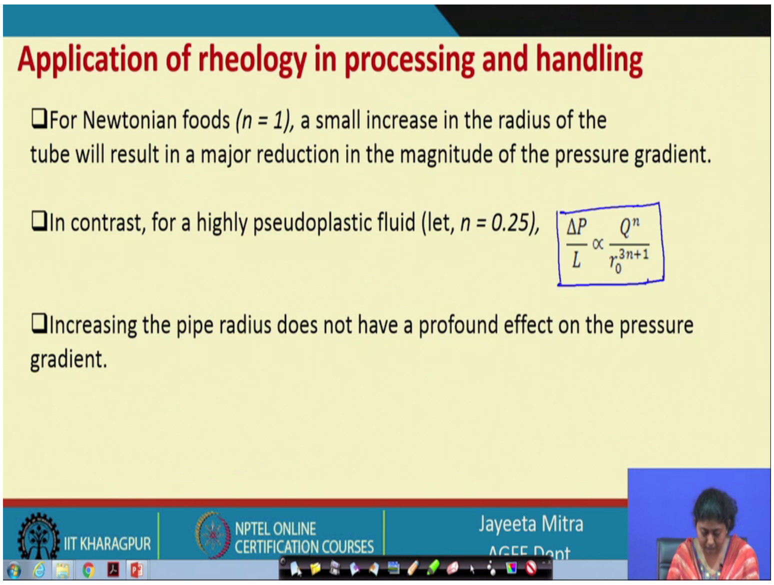

Now, for Newtonian food where in equal to 1, a small increase the radius of the tube will results in a major reduction in the magnitude of the pressure gradient. How we are getting this? When we relate the delta P with the flow velocity Q we are getting this kind of a relation.

So, delta P by L that is pressure drop across length or we can take unit length, that will be proportional to Q to the bar n where Q is the volumetric flow rate. N is the flow behavior index by r 0 the power 3 n plus 1. So, r 0 is radius of the tube, ok. So, if n equal to 1, and then this delta P will vary r 0 the bar 4, so, that means, small increases in the radius r 0 of the tube will result in major changes in the pressure radiant, because it varies with 1 by r 0 the bar 4.

Now if it is a highly pseudo plastic fluid, ok, where n is equal to 0.25, then increasing the pipe radius does not have profound effect on the pressure gradient. So, these understanding are important, because when you are handling any fluid food in an industry, and you want to design so, you need to see that what is the pressure drop, ok, or what is the radius and what the flow rate you want to maintain, ok.

So, all these are very related so, if you change one dimension consequently your other dimension will be significantly vary. And that also vary from different fluid so, you cannot take the same geometry same pressure drop for 2 different fluid, whose rheological behavior is totally different, ok. So, you have to design specifically each and every section for similar kind of fluid.

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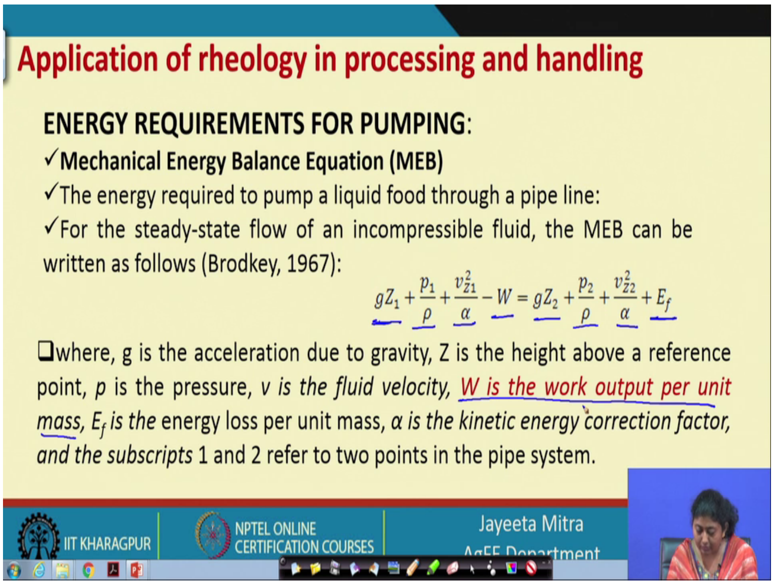

Now, another thing is energy requirement for pumping. So, you have understood about the flow velocity, you have understood about shear stress that we are getting at the valve or at any radial distance. And also you have understood that flow rate and relation of the flow rate with the, you know pressure drop. Right now energetic requirements for pumping that another important thing.

So, basically we will deal with the mechanical energy balance so, energy required to pump a liquid food through a pipeline, for this what we need, first we will write an equation for the steady state flow of an incompressible fluid where density constant. So, the mechanical energy balance equation can be written as g Z 1 plus P 1 by rho plus v Z 1 square by alpha minus W that is equal to Z, Z 2 plus P 2 by rho plus v z to square by alpha plus Ef, ok.

So, potential energy, pressure energy, kinetic energy, pump work and again the same for the different elevation if it there then energy or energy loss because of friction, ok. So, g is the acceleration due to gravity, Z is the height above a reference point. So, above difference point Z, we need to see the 0.1 and 0.2, where the elevations are to measure the potential energy changes, P is a pressure again 1 by rho P t 2 by rho rho is constant, because of incompressible fluids v is the fluid velocity.

Now W is the work output per unit mass. So, this is of our requirement of important, but we can calculate this only when we deal with all other terms. This all the terms we can calculate will put in this equation balance it and get the value of W. Ef is the energy loss per unit mass, and alpha is the kinetic energy correction factor. So, we know that there are certain values in the momentum transfer it has been given that what will be the value of alpha if it is a laminar flow, what will be if it is a turbulent flow, ok. And so, this is the energy requirement now one by one will see that how each term can be solved.

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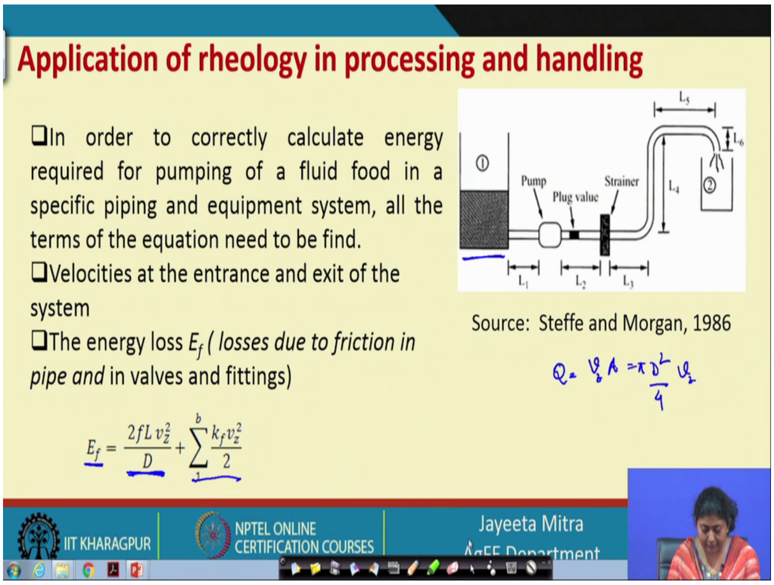

So, let us see the system is like this, ok, this has been taken from book of Steffe and Morgan, and here this is a source from where the pump is need to come this material to a certain amount of height at another distance in the section 2. So, section 1 to section 2, this pump is used to transfer the liquid food, ok, now in order to correctly calculate the energy required for pumping of a fluid food in a specific piping and equipment system. So, this system is a specific in the sense is dimension; it is you know diameter length of each section, what are the fittings? There like any bend or any fittings anyone valves, ok. So, all those should be properly identified and the loss of each section should be calculated.

So, velocity is at the entrance and exit of the system. That is the first thing we need to know. Now this we can calculate because if we know the volumetric flow rate, ok, volumetric flow rate Q if we know, and we need to know the diameter of the pipe in the inlet and exit, ok. So, then pipe area, sorry, pipe area that is pi d square by 4 into velocity, ok so, that will give you the volumetric flow rate. So, if you know the volumetric flow rate and we can get the velocity, right. Then comes the energy loss due to friction in the pipe and the valves and fittings.

So, energy loss that the term Ef, ok, so how we can calculate? Energy loss again we are we are getting it in the form of delta P by rho that is the friction head in that sense we are getting it. So, we need because of viscous loss, ok, and also other loss in the in the pipe friction, and the loss for the fittings right. So, this equation we are getting for the loss due to friction in the pipe. 2 f into L v z square by D, and this part that is how many number of fittings will be there that we have taken one to be; so, how many number of fittings will be there?

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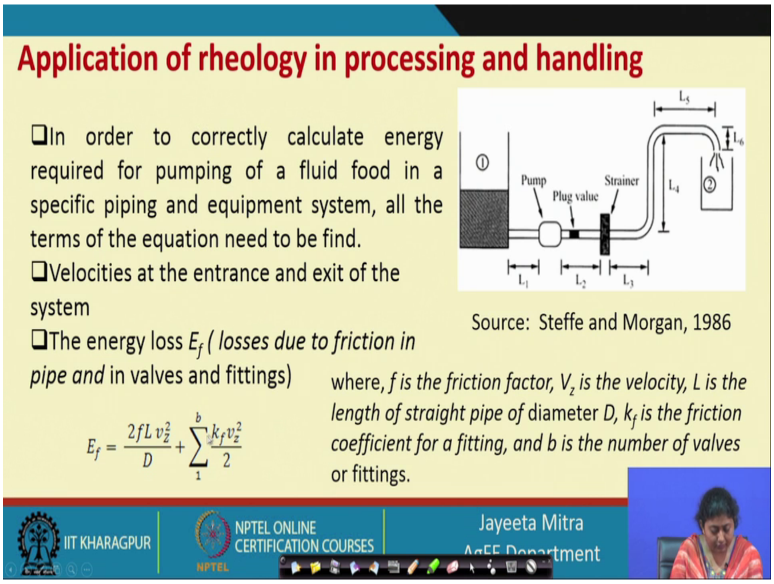

We will and all them and mostly the fittings the friction factor varies with the velocity head. So, v square v z square we have taken and with the coefficient k f that will give us the value of all the; I mean, pressure head loss in each and every fittings and will add this to get the total loss in the friction head, ok. So, if is the friction coefficient for a fitting and b is the number of valves or fittings, right?

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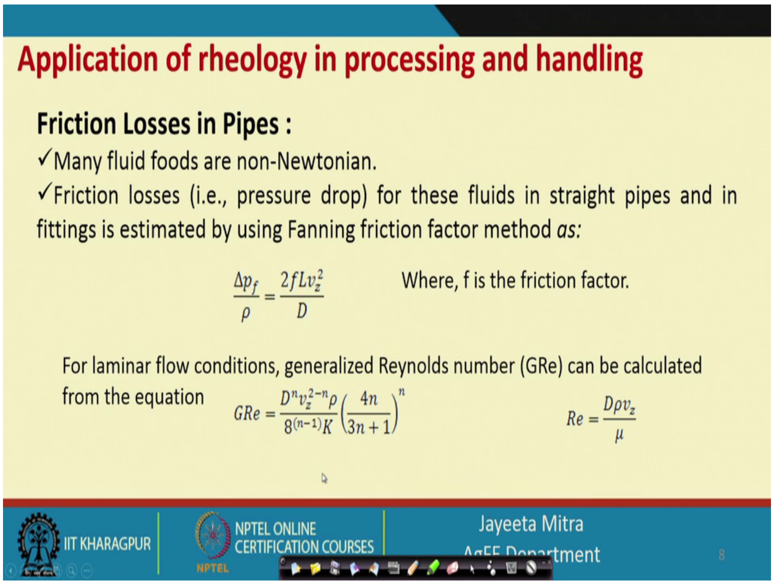

So, friction loss in the pipe many fluid foods are non-Newtonian. So, friction loss that is pressure drop for these fluids in straight pipe and in the fitting may be estimated using the fanning friction factor method, ok. So, then if it would have been a laminar flow, we can straight away use the Hagen Poiseuille equation and calculate the term delta P by rho we can get the head loss, ok, but since it is a non-Newtonian fluid and we need to calculate by the fanning friction factor method. So, delta P f by rho that is giving the pressure head, because of the friction loss that is equal to 2 f into L v z square by D so, if is a friction factor.

Now, for laminar flow condition, generalized Reynolds number can be calculated from the equation; this one, GRe generalized Reynolds can be calculated from the equation this one Grew generalized Reynolds number know that in terms of ruby, D by mu here v is the v z, ok. Now here it will be d to the power that is the diameter of the pipe to the power n into vz to the power v minus n into rho by 8 to the power n minus 1 K into 4 n in by 3 n plus 1 to the power n.

So, again the derivation you can get the momentum transfer course. So, this is the generalized Reynolds number and most of the cases when we are dealing with the non-Newtonian fluid, we need to use this generalize pronounce number to find the fanning friction factor, from the chart or if you want to use this for the further analysis.

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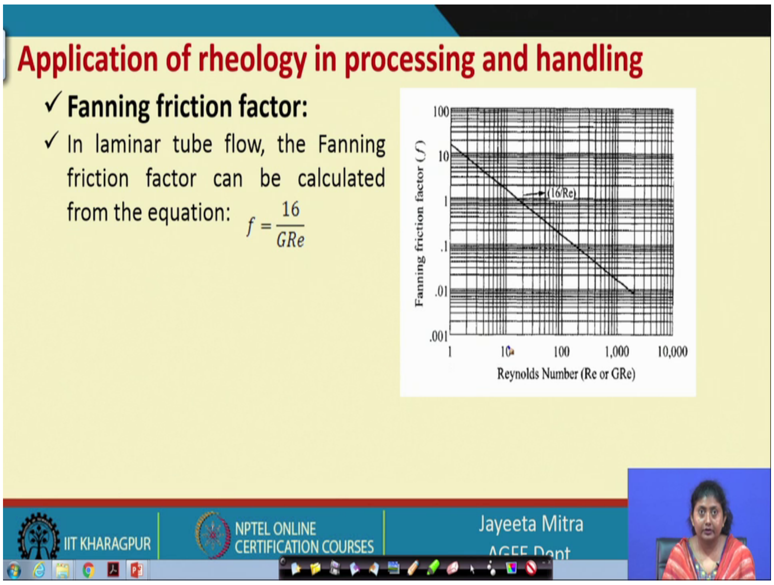

So, how we can do that fanning friction factor in laminar flow case inside it tube, this can be calculated as 16 by GRe that is generalized Reynolds number normally we do by 16 we write f as 16 by unary, here in the case of non-Newtonian it will be generalized Reynolds number.

Now, we can calculate the fanning friction factor from a chart which relates the Reynolds number, ok, either for the Newtonian which is purely Re or generalized Newtonian generalized Reynolds for the non-Newtonian and in the lamina region. That is why we are getting a straight line here in the lamina region.

From this chart we will see whether fiction factor f value is, and then will put into the previous equation we are calculation the pf by rho, and then we can get the friction loss. This kind of chart when we have first you know this has been developed by moody for Newtonian fluid in the laminar and turbulent flow, and it has been later prepared for the generalized Reynolds number or you know non Newtonian fluid as well.

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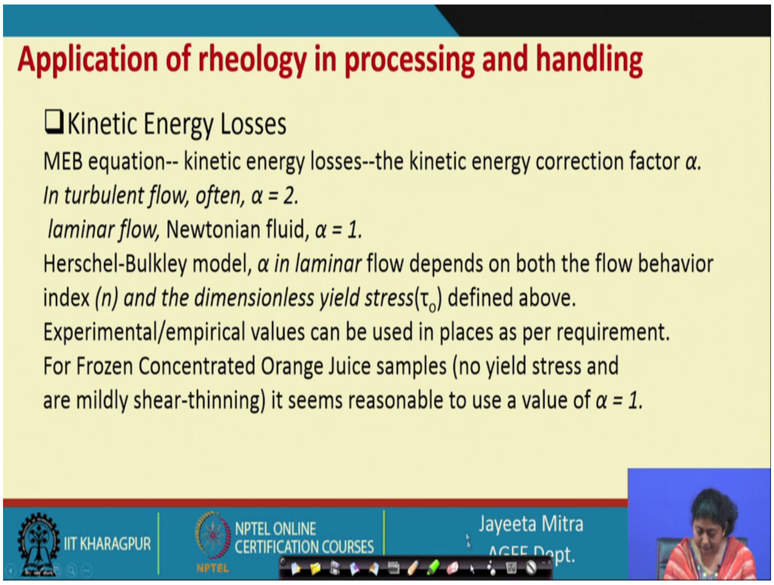

So, then there is kinetic energy loss term. So, what we do in the equation of mechanical energy balance, kinetic energy loss that is v z square by 2 alpha, we need to find the correction factor value properly based on the laminar flow or turbulent flow we often put this. And if it is a special case for Herschel Bulkley model, that alpha in laminar flow depends on both the flow behavior index, and also the dimensionless yield stress as defined above, ok.

So, that means, if we Herschel Bulkey fluid we know that they need an initial stress that that thing we have discussed in our previous class of the Herschel Bulkley model, which comes under the non-bingham kind of model. So, for all these cases experimental or empirical values can be used in places as per the requirement.

For you need to know first plotting the behavior of the fluid in the shear stress versus shear rate diagram, and to know that what kind of behavior it is, whether it is Bingham plastic non-Bingham plastic and what kind of then based on that you calculate the generalized Reynolds number and also find the alpha value accordingly. And finally, all this thing we need to put in mechanical energy balance to find the value of W.

So, there are few cases which are experimentally calculated that when frozen concentrated orange juice sample, which has no yield stress, then we have got the value of alpha equal to 1 for a case of mildly share thinning behavior.

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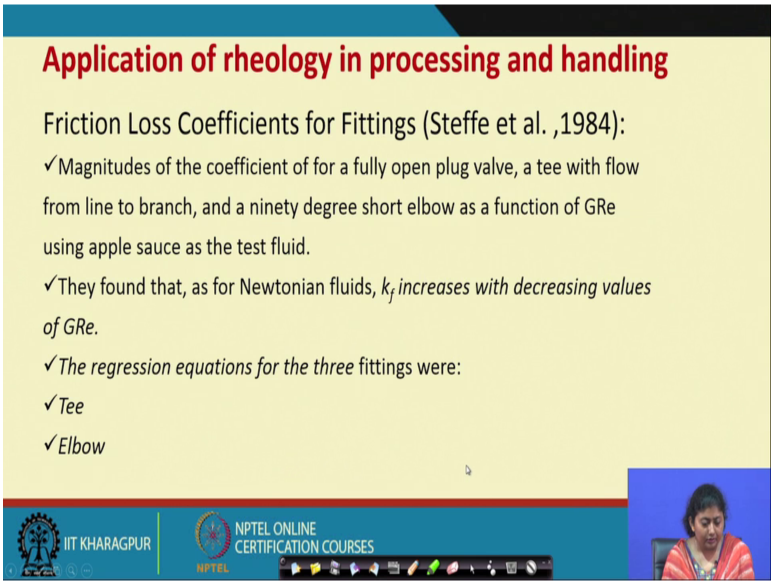

So, magnitude of the coefficient for a fully open plug valve, a Tee with the flow form line to the branch, because when we added to Tee join because that is bypassing one line from the main flow lines for a branch is creating. And a 90 degree shot Elbow as a function of generalized Reynolds number, ok. So, it has been it has been tasted on apple sauce, to calculate the friction loss coefficient for fittings.

So, as I said that based on different Reynolds number or different fluid all this coefficient will change, the cell will be changed. So, here in this particular case for we have found for the, for Newtonian fluids, k f increases with decreasing the value of generalized Reynolds number. So, k f k f increases f is a k f is the coefficient that we use for the friction factor, we use k f into v square by 2, and sum it for all the fittings that we have.

So, the regression equation for the 3 fittings that we have got that is k f equal to 30.3 GRe 0.492. K f for the Tee joint we are getting 29.4 GRe minus 0.504, and for the 90-degree Elbow joint we are getting k f equal to 191.0 generalized Reynolds number to the power minus 0.896.

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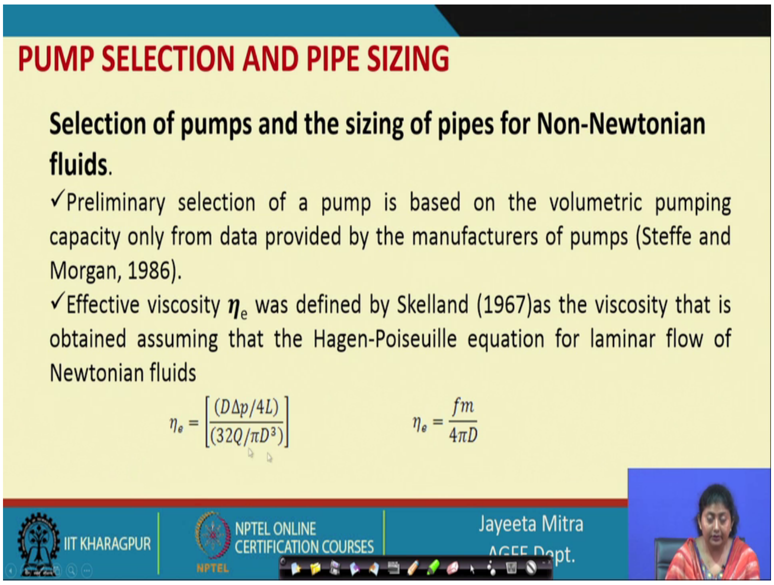

So, selection of pumps and the sizing of pipe for non-Newtonian fluids. So, preliminary selection of a pump based on the volumetric capacity of the pump. And often this kind of thing we can get from the manufacturers data they provide this with this pump. Also the effective viscosity is related to the efficiency of the pump, ok, this kind of graph has been given or this has been developed to identify the effect of viscosity on the pumping capacity, right. So, this viscosity with the flow rate can be prepare assuming that the Hagen Poiseuille equation for laminar flow of Newtonian fluids, ok.

So, if we used that one we are getting this effective viscosity as D delta P by f 4 L by 30 2 Q by pi d Q. Or if we try to related this mass flow rate we can do it by in eta e as is equals to f friction factor into m by 4 pi D, ok. So, this we can relate the flow rate and viscosity effective viscosity.

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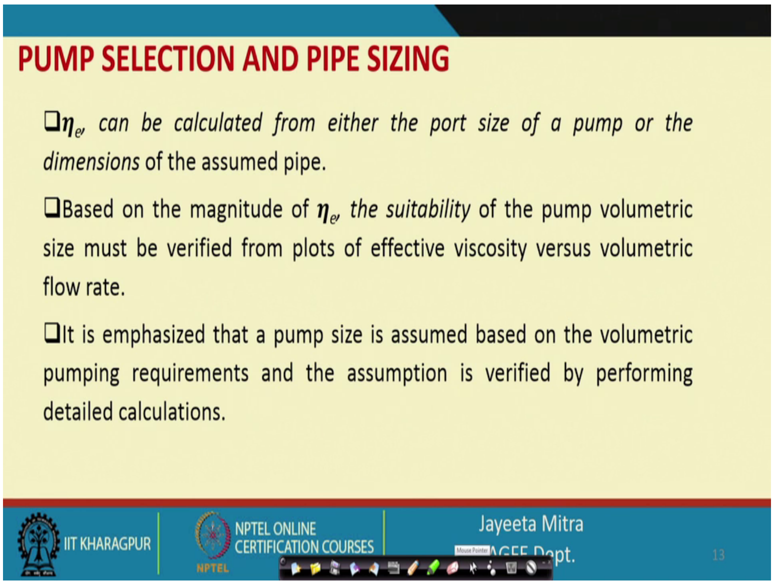

And effective viscosity can be calculated from either the port size of a pump or the dimensions of the assumed pipe, ok

So, if suppose we know we know the pipe and we can calculate the flow is laminar or turbulent, then based on that we can calculate eta e or we can straight away use the Hagen Poiseuille equation, for that pressure drop and then we can calculate the eta e. Now based on the magnitude of eta e the suitability of the pump volumetric size must be verified from the plots available of effective viscosity verses the volumetric flow rate.

So, it is emphasized that pump size is assumed bases on the volumetric pumping requirement, and also this assumption should be verified by actual calculation, right, using that in actual case.

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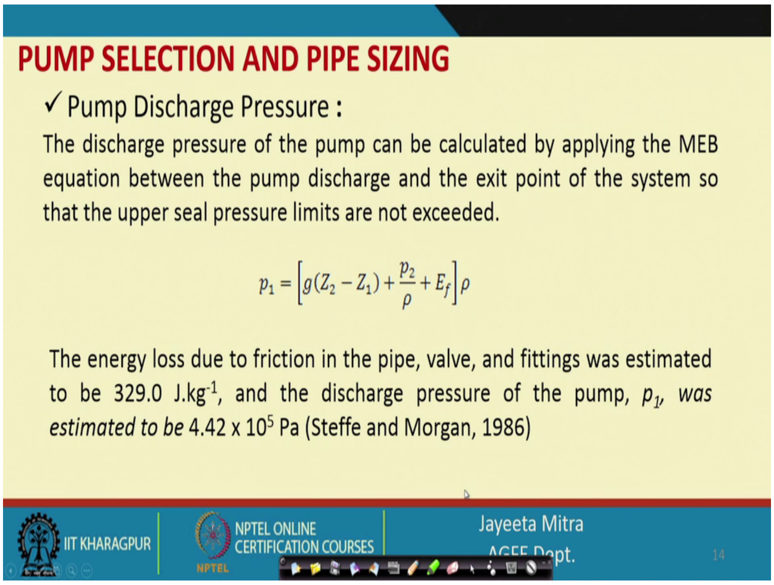

And last is a pump discharge pressure if you want to calculate that. So, using again this equation, we will take P one that that is that is our requirement that is what will be the discharge pressure we want to calculate, where P 2 that is our atmospheric pressure we can take elevation to what to what you know transfer in that we can calculate total energy loss because of friction. We have to calculate prior because based on that value that depends on many factor as I said that why friction and all the fittings.

So, that need to be calculated first and then we can find what is the value of this discharge pressure, ok. Ultimately we are calculating it again from the mechanical energy balance and it is coming for this particular case where Ef value is 329.0 joule point kg and it is coming 4.42 into 15 Pascal.

So, this is how the understanding of fluid behavior will to help to eventually design the whole system, starting from the velocity distribution, then residence time in a processing channel volumetric flow rate, then pressure drop then the whole energy balance pump requirement volumetric flow rate requirement of pump, ok, and then finally, the discharge pressure.

So, here we will stop, and in the next class we will start the viscoelastic food.

Thank you.