Polymers: Concepts, Properties, Uses and Sustainability
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Week 9
Polymer Processing and Recycling Techniques

Lecture-69
Polymers - Uses

Hello, welcome to the discussions related to the polymer processing and recycling techniques in this course on polymers. In this lecture the focus will remain on the applications and we will review 2 specific polymer processing operations.

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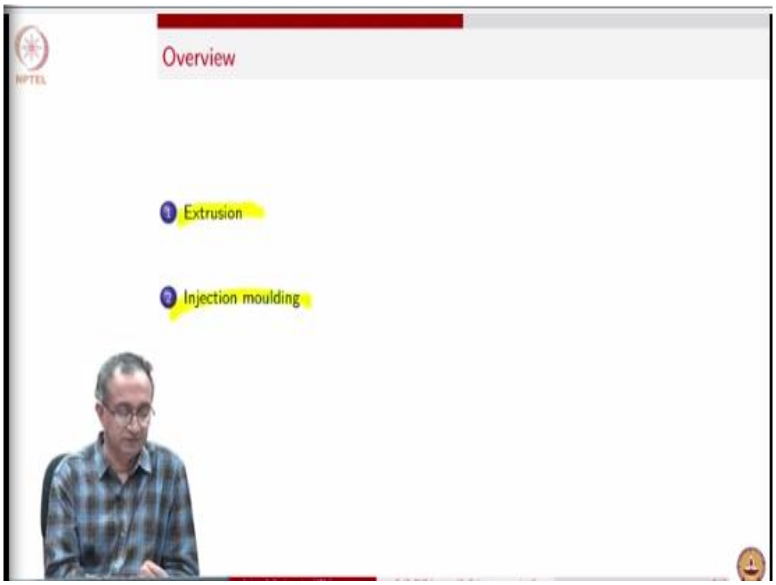

Namely extrusion and injection moulding, both of these are extremely common processing operations which are used in polymer processing.

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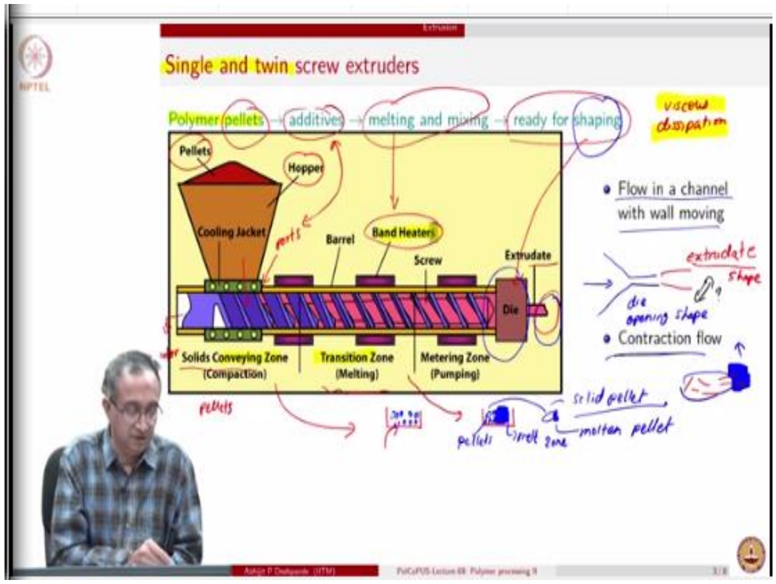

The extruders can be single and twin screw we will discuss twin screw extruder later on which is also a very efficient mixing device. In this slide what I have shown is a single screw extruder. The idea of extruder is to start with pellets on one hand and these are usually cylindrical pellets few mm diameter few mm length. And they are fed through a hopper onto a screw and then of course we can add other things also. So, there will be other ports for adding additives on this, and additives of course are for stabilization or any other feature that is desired. And if we let us say are making of length then we will have to have pellets of both of the polymers. If we are making just one polymer homo polymer then we just have a one single pellet. But in both the cases we will have mixing and melting involved because there are additives and a single polymer or 2 polymers being mixed.

And once melting and mixing is happened then the overall polymeric system is now ready for shaping. And the shaping operation then is done using the dye and finally what comes out is called the extruder. So, if you look at it initially they will be only pellets and that is why it is called a solids conveying zone. In this case what happens is the screw which is there is rotating because it is connected to a motor. And so the screw rotation is a very important variable at our disposal in order to optimize this processing operation. Because faster is the screw rotation that implies that faster is the delivery of pellets and the compaction that is involved because we are pushing the pellets against each other.

At the same time we also will have heating that is going on because melting is involved. So, given that melting is involved some amount of heating is done. However given that this material is getting compacted given that one layer of fluid is rubbing parts the other layer of fluid or frictional forces or viscous forces are involved. In all of these polymer processing operations we have significant amount of viscous dissipation. So, some amount of heat is being generated due to the action of flow that we are forcing the polymer to undergo. And so as material comes proceeds further we have this transition zone where temperature as increased, so that the pellet start melting. And if you look at in and let us say we look at this from the side between basically screw. So, this screw is rotating and therefore what we will have is the pellets of the polymer. So, initial stages these pellets will just continue to rotate because the screw is also rotating. But beyond a certain time once it comes to, so this will be in the solids conveying zone, when we come to the transition zone then what we will have is part of the pellets may still be there and the other part of the screw may already have a melt.

And even surrounding each and every pellet if you look at little more carefully you may have a pellet part of it may also be molten. So, therefore solid pellet and molten pellet, this is at a single pellet level or we could have melt zone and pellets. So, in extruder by definition we have this multi phase flow where there are solid pellets and molten polymeric melts moving simultaneously.

And if let us say the mixing operation also involves fibers then you can see that what happens is the polymer surrounding the fiber the is going to melt but the fiber itself maybe glass or a natural fiber like cellulose or jute, then that is not really going to melt. And so what that leads to is basically breakage of fibers. I will draw this picture in a magnified scale.

So, if you have a pellet and there is a fiber everywhere in the pellet and so what happens is part of the pellet has molten and so I will have to draw the fibers in a different colors, so that we can see them. So, let us say this is a fiber then there are fibers inside the pellet also. Now the molten part can flow while the solid part the pellet embeds the fiber. So, you can see that this fiber is going to experience a shear force because the molten fluid is going to move and flow while the solid pellet cannot move. Of course the sold pellet can rotate itself but the rate at which the solid pellet rotates and the rate at which this fluid is moving can be different. And then therefore there is a shearing action on the fiber, and what will this lead to the breakage of the fiber.

So, whenever we are making short fiber composites in the pellet we may have a fiber which is let us say 5 mm or 3 mm long. But in the extruder the fiber size will be 2 mm or 1 mm and all of it depends on what happens at a single pellet level and how this melt zone is formed and how does it shear next to the pellet and so on? So, you can see that from the importance of analyzing the final product what happens to each and every section how are solids conveyed?

How do solid start melting? How does the melt flow is very important. And then of course the final part is the dye, and dye is necessarily much narrower than whatever is the barrel and the screw opening there. Because we force the material through a narrow dye and do the shaping operation and finally get the extruder. So, you can see that based on this description the two classic problems of fluid mechanics are flow in a channel with wall moving.

So, this is where the screw is rotating and because of which polymer is also moving. So, this is like saying that I have a material between two plates and one plate is moving because of which the polymer is also moving. The other problem is that of the contraction because we have basically polymer being pushed through a narrow opening, so that we get the extruder. And one of the important aspects of extrusion design is what is the shape of the extruder?

And what is the shape of the dye? So, the dye opening shape and the extruder shape how are they related to each other? And that is an important part of design; we will see later on that extruder shape is not exactly the same as the dye opening. Because of as soon as the polymer comes out because of the elasticity macromolecule where force to go through a very narrow opening. And so contraction flow is very significantly influenced by the segmental mobility and the segmental flexibility that is there in the polymer, when we are forcing it to go through the narrow opening the polymer molecules can get stretched. But as soon as it comes out, as soon as the extruder is formed again there is no opening there anymore and polymer segments can go back to their earlier confirmation.

And so this elasticity will induce a shape in extruder which is different compare to the opening. So, you can see that an example process such as extrusion involve so many intricacies which are related to phase transfer because solidification to melting is involved. Then it involves flow and shaping and stretching and shear flow, an extensional flow, flow through contraction, flow through a pipe, flow through a channel. So, many different examples are involved and post extrusion now the shaping can be done, you can stretch it again and then finally cooling has to happen, solidification or crystallization or vitrification.

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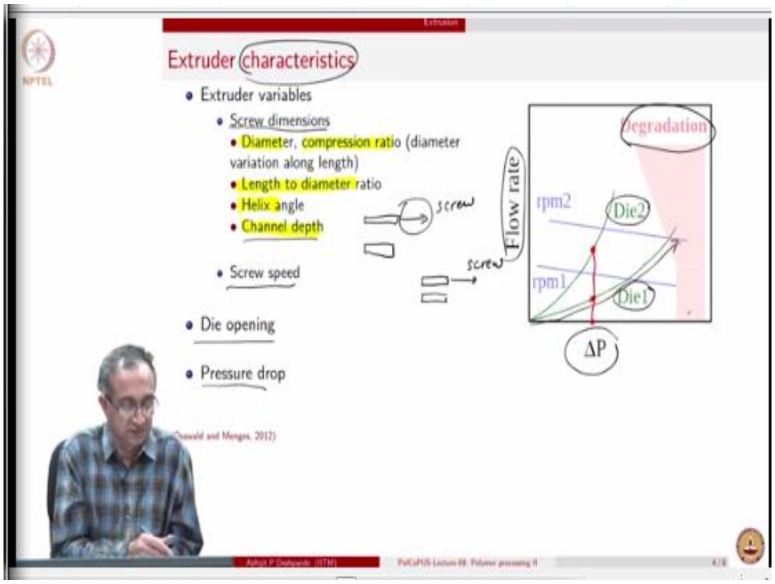

And so, in this operation there are several parameters which are important, based on the description that I give, we already know that you know screw dimensions will be very important. The diameter, the compression ratio, this compression ratio is important because that is what we will determine how the conveying of solids happen and how does the transition zone melting happens? Because basically with this narrow opening becoming narrower the solids get pushed and then through viscous dissipation and the heating heaters which are there, we can have melting of the polymeric pellets. And so therefore compression ratio as important, the length to diameter ratio of the screw is important. Because that determines the how these different zones are separated from each other.

The angle that determines again how is the pumping action or the screw conveying action happening? And then the channel depth of course determines the overall amount of material that is available. Higher the channel depth it also implies that the strain rate will be lower and to explain this, you can just think of this problem where let us say if I have a flat plate and I pull the top plate with certain velocity there will be a certain strain rate in this. Now I take the same two plates but now I have much narrow or opening and I pull the top plate with the same velocity. So, this is equivalent to channel depth because we could think of this as the screw moving at a given velocity. But if the channel depth is less then the strain rate will be higher because strain rate in all of these cases is the velocity of the screw divided by the channel depth.

So, therefore that determines the mount of strain rate and we already know that strain rate influences the flow behavior of polymeric materials very significantly. And so screw speed and channel depth together determine the strain rate with the material. Then finally the dye opening and the overall pressure drop because of pumping actions determined what is the overall behavior of the extrusion operation. And generally this can be shown using what is called an extruder characteristic. So, we can look at flow rate because we are interested in how much amount of polymer we can process for unit time. So, that is determined based on flow rate, we would like to make parts as fast as possible and so therefore flow rate should be as high as possible, however there are limitations.

We can apply higher and higher pressure and again achieve this higher and higher flow rate. But when we go to extremely high pressure then and we will say have degradation set in the material chain sessions and reactions like that can degrade the polymer material. Now in this basically flow rate versus pressure drop can be part of when we think in fluid mechanics the standard problem we solve is pipe flow. And in a pipe flow if there is laminar flow then we know that flow rate is proportional to pressure drop, so we will get a straight line. But here we have polymeric materials which are non Newtonian as well as we do not have a straight forward pipe. But we have similar to a pipe whose cross sectional area keeps on decreasing because remember there is a compression ratio. So, therefore generally pressure drop increasing will change the strain rate and therefore change the flow rate non linearly.

And this is the kind of a behavior that you will obtain for one particular dye when you change the dye size you will get a different flow rate versus pressure drop characteristics. Looking at this graph can you make out which diameter of dye is higher is dye 2 diameter high for dye 1 diameter. To think of it you can just post this question that at the same pressure drop which one gives me higher flow rate and which one gives me lower flow rate and why? So, I am sure then you can quickly that dye 2 or to have a bigger opening because I get much more flow rate from it. And similarly the screw speed also determines how much is the amount of material that I get. And at different pressure drops and screw speeds we will again have different characteristics. So, generally this kind of a characteristic is drawn to each and every for every set of extruder system. And then we can decide which dye to use? Which rpm to use? How much ΔP to use? And what kind of production rate we will be get using the analysis of such characteristic curves.

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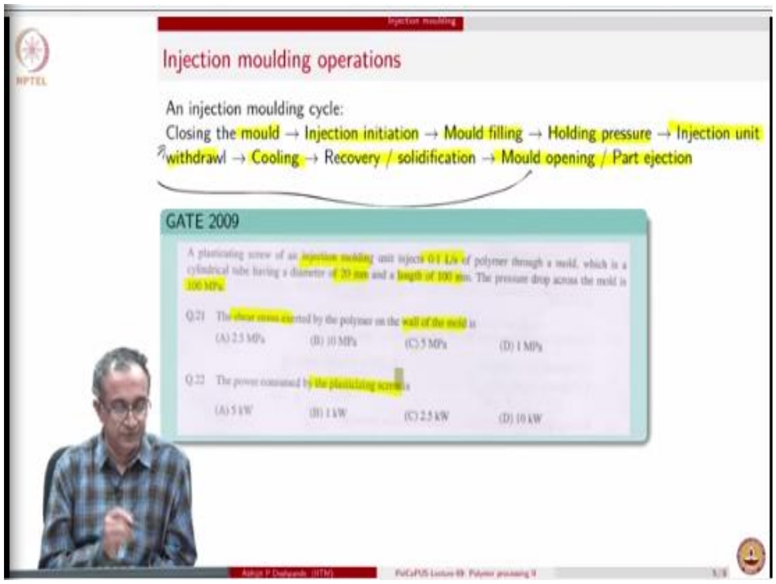

Let us shift and now look at the injection moulding operations. Injection moulding is a cyclic process as suppose to the continuous process of extrusion where we saw that melting happens and then it gets extruded and keeps on getting pulled and then therefore it is a continuous operation. Injection moulding on the other hand is a cyclic operation, how is it cyclic? What do we do?

We start with a closing the mould, as soon as we close the mould we imply that mould can be filled. So, therefore then injection can be initiated, when we initiate the injection, mould filling happens. And then once the mould is filled we hold the material per sum amount of time, and then we can withdraw the injection units. And simultaneously start cooling the sample, so that recovery and solidification happens. As soon as solidification happens mould can be opened and part can be ejected. So, this is nothing but again opening and so the next stage again will be to close the mould and so it is a cycle which can continue. And strength of injection moulding is all of this can be done in couple of seconds that is how fast the injection moulding process is. And the design of injection moulding involves several calculations again in terms of pressure drop and flow rate.

And this exam question highlights that if you have an injection moulding unit which delivers a certain amount of polymer. And the dimensions of the tube in which the deliver is happening is given and also pressure drop is given. Then can we have an estimate of what is the amount of stress that is generated by this polymer because the mould itself is not moving. So, what will be the amount of stress that is generated and then whatever is the amount of power that is required for the screw to actually convey the material to the moulds.

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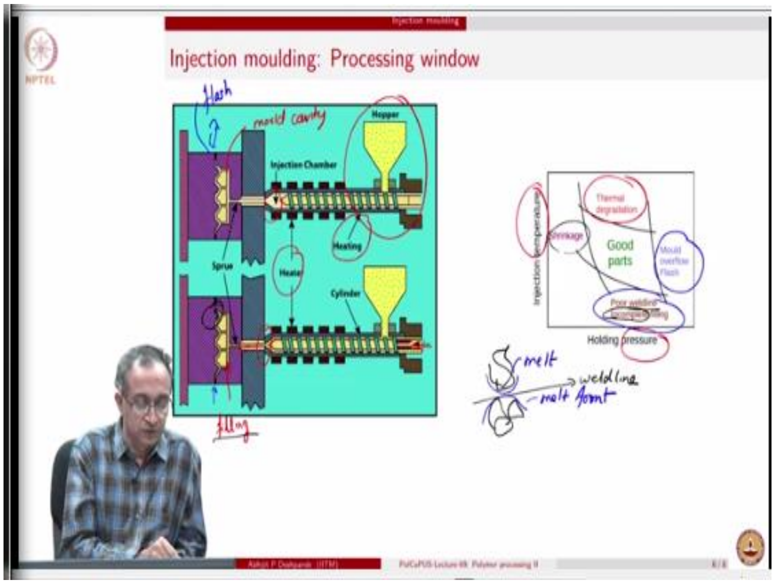

So, you can think about this while we discuss the injection processing operation in little more detail. So, initial part of the operation again looks like the extrusion where through a hopper pellets are fed in this case though we already have a set of pellets which are mixed. So, the role in this case of the injection unit is to just make the polymer into a molten form, so that it can be deliver to the moulds.

And as soon as the mould is closed then what we have is there is an injection chamber in which fluid will accumulate. And then when the screw moves forward the injection material can then flow and then fill the gap. So, you can see here that the mould is empty, this is the mould cavity so to speak in which the fluid has to come and flow, so mould filling is happening. And again to melt the polymer, heaters will be there and the barrel cylindrical barrel is there. And then there is again a narrow opening through which the polymer will have to flow and then flow into the mould. In this case what is the complexity of shape in the mould itself is also very important and for toys or various other things the shape can be very complex. In certain section the part can be very thin some other section the part can be very thick and so all of this flow has to happen and again there is an operating window.

And that operating window can be thought of in terms of pressure and temperature. If we change the temperature of moulding then the viscosity will be lower, flow behavior may be easy. And similarly by applying higher pressure we may be able to quickly do the process, however there are again limitations. If we have too higher temperature then thermal degradation can take place. if we apply too much of pressure then the mould can overflow. Remember that there is always this mould closing and the two parts of the mould are coming and closing. If we apply too much of pressure then there will be narrow openings in which the mould has closed material will starts flowing. So, there will be what is called a flash which implies polymer coming out of the mould which is closed but it cannot be ensured that it is completely sealed or leak proof.

On the other hand if you apply less temperature then what happens is the polymer segmental mobility and macromolecular motion is not very fast. And when polymer comes in contact with another polymer melt, so this is let us say melt front and this is also melt front. And when they come in contact with each other the macromolecular segment from this and micromolecular segment from this should intermingle for you to get a good well line. In fact no well line will imply that there is perfect mixing but at low temperature what happens is macromolecular flexibility is less.

And therefore we get a well line which is quite prominent and that becomes basically the weak part. Or sometimes the viscosity can be so high that the filling is incomplete. In some places the polymer does not reach. And in that case we will have incomplete filling. So, the filling process itself is not very efficient. So, again low temperature is not desirable if we maintain two lower pressure then again there once the part comes out there will be significant amount of shrinkage because maintaining pressure and allowing stabilization of the overall polymeric material is important.

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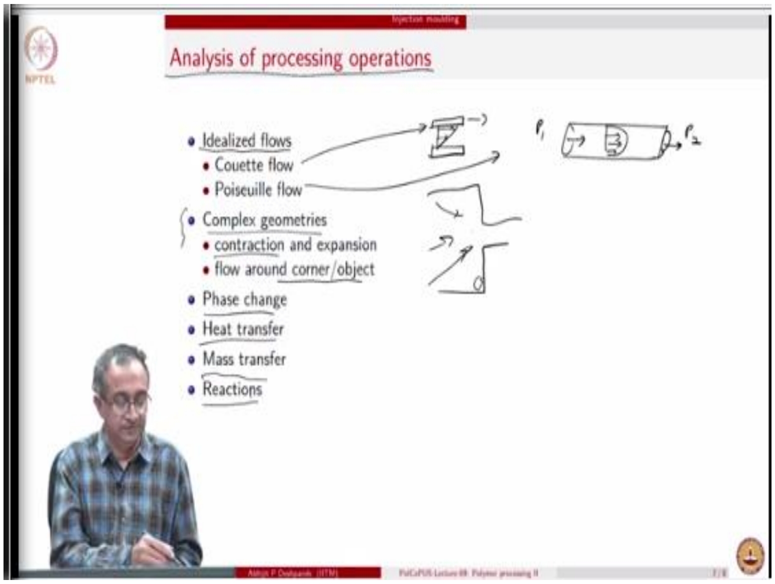

So, with this we have seen 2 important processing operations extrusion and injection moulding. And we have seen how flow is very important, and therefore analysis of these processing operations in terms of flow behavior involves some of these features. We look at flow in an idealized sense, we look at a couette flow which basically implies taking the material between a moving solid surface, so this is couette flow.

We could also look at Poiseuille flow, in which case we have a cylindrical pipe and then we impose a pressure gradient and force the polymer to flow through this. And in this case of course we may get a velocity profile where it is maximum at the center and 0 at the surfaces. So, these are 2 ideal types of flows and you can see both of these are important when extruder screw is moving then we have a couette flow.

When we have the pumping operation in which pump is creating pressure then we have Poiseuille flow. Because extrusion dye when the material is coming out, pressure is very high in the extruder because we have all these screw action and fluid is basically being force to move and therefore pressure is extremely high. And the other side is atmospheric pressure because that is the extruder where the polymer has come out. And so we have a pressure gradient and so flow through the dye opening can be analyzed using Poisecuille flow. And of course we have complex geometries, so there is contraction and expansion. Because as soon as the material comes out in the mould it is like expansion but it is going through the extrusion dye then there is contraction. So, both contraction and expansion flows are involved flow around corners and objects are involved. We can have an opening like this contraction where fluid is flowing and we can have these corner and flow around corner maybe very different. In fact there may be a stagnation zone where polymer may start solidifying or degrading and once in a while that polymer joints the flow and therefore it comes out that will compromise the performance of the part.

So, all of these complex geometry flows are very important additionally we have solid to liquid phase transition. If there are some volatiles in case of foaming operations we will definitely have a glowing agents, so there is phase change there also. Heating and cooling are important part in terms of melting as well as solidification. And if let us say crystallization or polymerization are happening simultaneously those bring in heat release whenever there is polymerization happening. Heat absorption is there if there is melting happening. So all of these involve basically transfer of heat. And then we have mixing of small molecules with macromolecules, mixing of one macromolecule with another macromolecule, mixing of a same macromolecule in a mould where well lines can be formed. So, mass transfer is also extremely important and finally of course we can have reactions. So, if we have to analyze processing operations, these are all the features which need to be looked at very closely.

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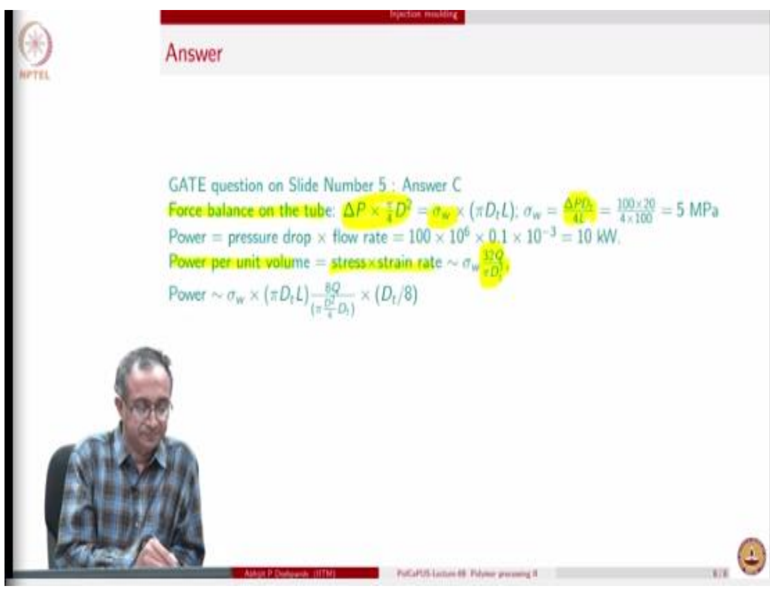

And so with this we will close this lecture which talked about extrusion and injection moulding as the two most important operations. And the question related to the injection moulding operation is basically based on a force balance where the pressure acts at entry and exit and therefore it is related to the cross sectional area where the pressure is acting. And then the transfer of stress between the polymer melt and the surrounding tube is based on the wall stress.

And so wall stress can be calculated based on this and then the power per unit volume is nothing but stress into strain rate. And strain rate for this kind of pipe flow is again given. So, therefore based on this we can run calculate what is the power that is required.

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So, with this we will close the lecture, thank you.