Rheology and Processing of Paints, Plastic and Elastomer based Composites
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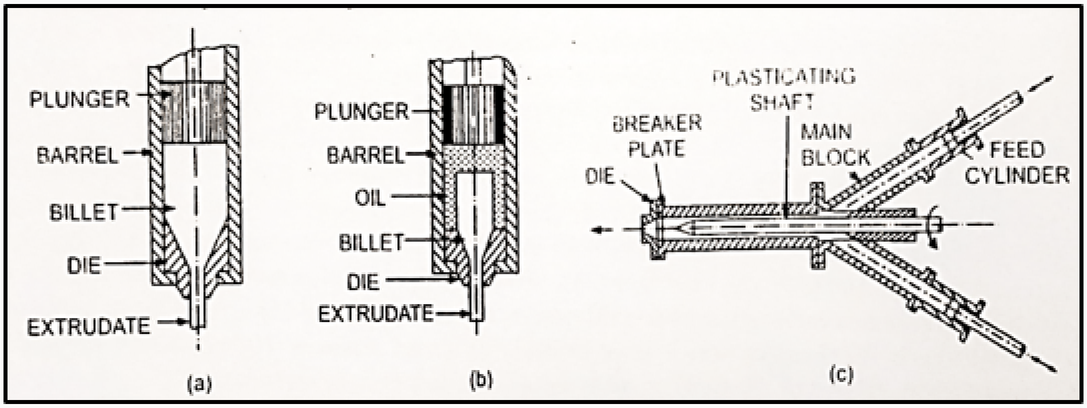
Lecture 39
Extrusion

Welcome to the NPTEL online certification courses on the rheology and processing of paints, plastics, and elastomer-based composites. Today we are on week 7 and lecture number 7.3 is all about understanding basic conceptions and basic fundamentals on extrusion which is one of the major you know processing or heart of the polymer processing you can say. So the concept will give you a very very crude introduction there and about different types of extruders specially in the form of discontinuous continuous, screw based extruders which is mostly important, basic features single vice versa twin screw extruders bit on the assembly part of it and then flow throughout although we are not going to all the sections like say starting from feed as I mentioned it to earlier this feed to compression to the metering let us confined to the metering section just before it is being extruded through the die or die land before it goes through the die land and then that part we will try to see and then finally, little bit of addressing some of the regular problem that it happens for the extrusion. Once again L by D ratio is very important as I mentioned it to you right for plastic extrusion we are for to have a very high L by D ratio on the contrary for our extruders should be smaller and also I talked about if you want more you know mixing action you need to have a intermeshing sort of a design. Sometimes you have a volatile things in order to get rid of trapped air or vapor you need a venting system okay and there are different types of you know breakers, screen, die, reciprocating screw all these things you just stick to the keywords listed here and before really going into that you can go browse through the literature and find out although at the end I will prescribe you some of the books where from you can directly get those.

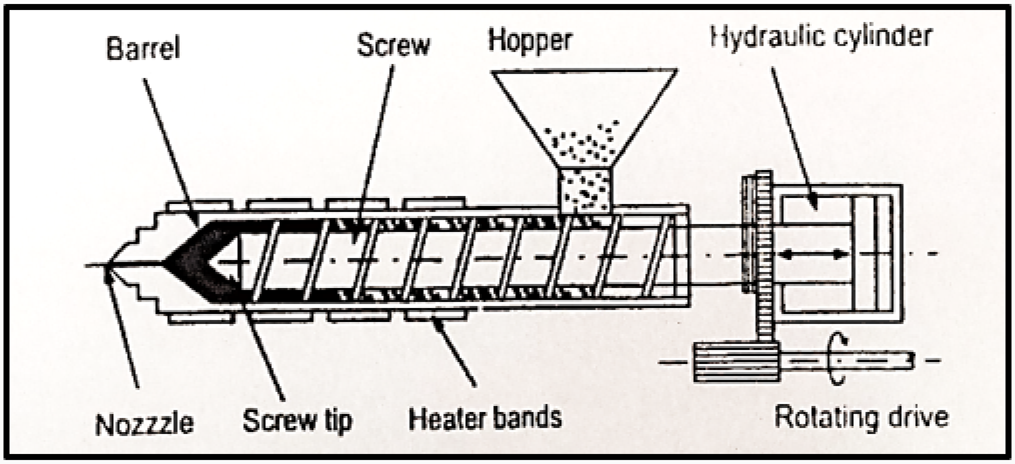
Again to introduce as an introduction all polymers undergo extrusion processing at some stage or the other before the final polymeric component takes the shape, but I will not say for rubber it is always the it has to go it may not be from mixing you can go through the calendaring and then that particular component is made ready okay, but of course some of the components like I said trade of part of it, bead wire part of it that you cannot do other than extrusion process. While talking about calendaring I told there is a thickness limitation because porosity will be generating if you try to make it more in that case extrusion solves the problem okay. So again as far as extrusion generalized extrusion for polymers keeping aside rubber alone general way it can be either continuous or batch or discontinuous type. Although when we talk about extrusion we always try to see it like a continuous process fades then the screw conveys and goes through and through and then you get the final shape as far as rubber is concerned you get into the pre-shape and then it goes through the vulcanization channel that is the story of it okay.



Ram extruders (a) Single ram -Direct solid state, (b) Single ram-hydrostatic solid state and (c) Twin ram extruder

It can be either one component or it is a combination of extruders and then there the flow line will merge okay. So that way you make it in a single go you can have two three components extruded together okay or else you can have a cross head extruder in one component may be your steel wire and the other the flow of the polymer will submerges on that giving rise to your I mean coated wires and you get those manufactures for bead wire as I mentioned it to you. Say for example cables is another form of it which needs a continuous you know cross head extrusion. So single, double, multi that can also be the flow channels but let us try to understand in a singular flow channel how the flow happens. So when I talk about a continuous type of extruder it develops a pressure from the feed to the you know once it is getting coming out of the die okay and by a continuous forward flow of the material okay.

So that is what is a continuous I mean the basic sense of it but batch is also possible. So for example if you have a reciprocating action other day I was talking about injection or transfer you remember I was talking about a screw which conveys as well as then it you know gives you thrust as a ram or plunger. So in that case it is not a continuous extrusion it is a batch type okay. So in that way discontinuous extruder once again can be ram type. So ram has its advantage as I told you it has you know pressure loss or back flow is quite quite less.



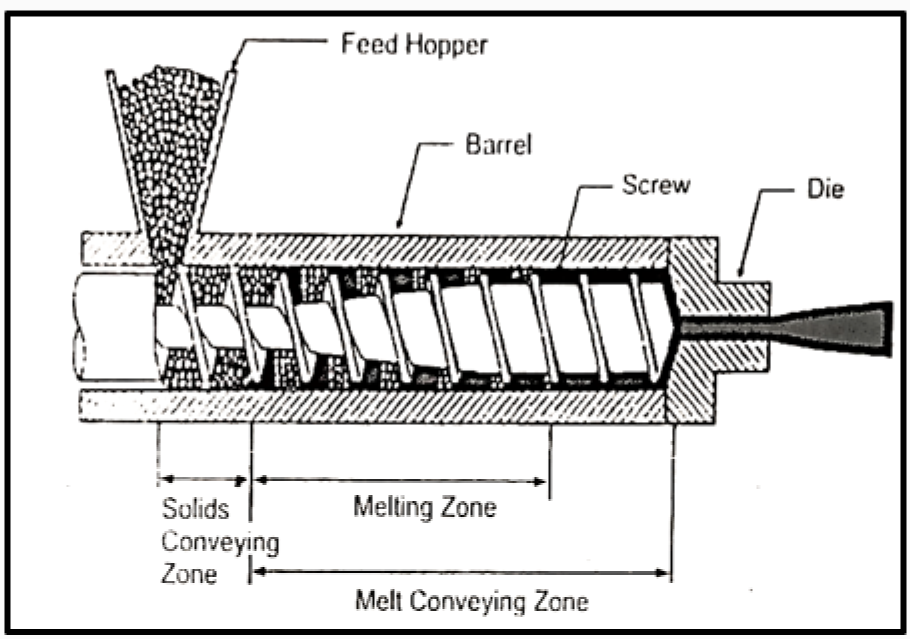
Schematic of a reciprocating screw plasticating unit

So you can generate high amount of pressure if it is required but screw has its own advantage in the sense it can give you optimum plasticization heat transfer transverse mixing okay. So that those are the advantage but of course if you even if it has a reciprocative action you cannot generate as high as that pressure you can otherwise generate using a ram type or plunger type of extruder. So here you go you have three different distinct type is a single ram direct solid state even a you know metallic component like lead also you can extrude by this process by the way it is not always polymer. So other case it is a single ram hydrostatic solid state what is the difference you have a oil in between that thrust is being transferred to the oil ultimately gives it to the final go for generating that pressure basically. And of course the twin ram is also possible like you see you can you have a two rams that ultimately gives you the final extrusion pressure okay.

So this is also another type okay. So these are not actually very relevant to rubber extruders extrusions but these are mostly done with a ultra high molecular weight polyethylene for PTFE for HDPE that kind of either using or you know commodity plastics also you can use this kind of extrusion as I told some of the extruders can be used for soft metal extrusion also for your information. So now in single ram extruder one ram is used to apply very high pressure to extrude the material okay and these are categorized into direct solid state is called DSS or hydrostatic solid state ram extruder always already I explained you what is the difference between these two one has a interim oil through the while the pressure is being transmitted okay. So solid state ram extrusion is used to impart high degree of molecular orientation normally it is done little bit lower temperature than you know melting temperature. So as a result what will happen you have little bit more molecular orientation and as a result it gives you highly improved mechanical properties say tensile strength okay.

So this is what is being done okay. Both of these methods are performed solid rod of material or a billet being subjected to pushing force directly by the plunger in DSS extrusion and through a lubricating liquid in HSS as I told you in between there will be some oils like linseed oil or some sort of a oil will be present okay. So now this is a diagram of a reciprocating screw extruders okay. You see from the hopper to the here in the in that in the final nozzle part tip of the you know screw you see this is the hydraulic cylinder and this is the rotational motion it is imparting okay. So the reciprocating screw extruder are basically single screw extruder okay, but the screw acts as a plunger as well.

I told you while talking about the transfer molding or injection molding part okay. Remember reciprocating sort of a geometry for injection molding machines I highlighted towards the end. So conveying melt and plasticizing the polymer. So these two are the role of the screw usual rotation and secondly injection is by the reciprocation. So that is how you finally achieve that by combining them.



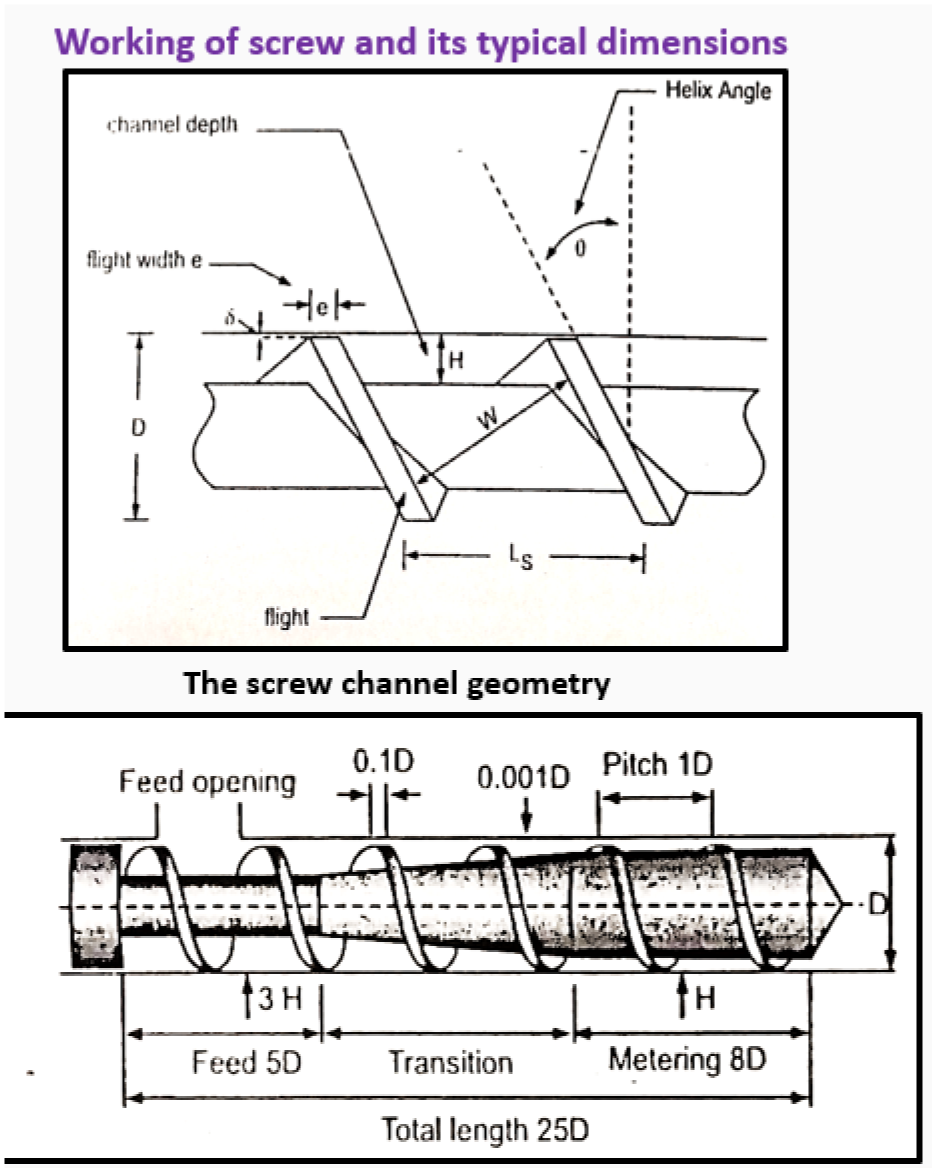
Schematic of Single-screw plasticating extruder

State of material in the screw channels

Now coming to the continuous extruder which is quite common both rubber and plastic extruders. So it can be screw extruder or drum type of extruder generally although the first one is very common quite common. It can be a single screw extruder okay or it can be multi screw extruder especially for the plastics as I mentioned it to you the twin screw either co-rotating or counter rotating those are the heart of the mixing in plastics. While your internal mixture or inter mixture or manberry was the heart of it in terms of mixing. So those are actually used for making the you know polymer you know mixing with the pigment mixing with the other polymer and so on and so forth.

The Disk extruder is the second one have not been able to match the performance of a screw extruder that is what I told you in polymer processing and that is the screw extruder both single and twin screw are the most popular choice for polymer processing technology always. So screw extruders as I mentioned it can be either single screw only one screw to process the polymer twin screw are mainly two types of as I said co-rotating this is two screws are rotating in the same direction clockwise manner. The second is a counter rotating one clockwise other is the you know anti-clockwise. So again it can be intermeshing intermeshing means the radius of rotation that this slides will try to overlap. So you have a additional you know high intense mixing action you have a non intermeshing where you do not know you want only little bit of you know mixing not that intense dispersion and partially intermeshing type.

Now multi screw extruders are not very common though but those are having more than two screws are gear pump. Gear pump extruder actually is used for the rubbers which are apparently difficult to extrude viscosity is still high. So screw conveys and then you have additional gear and that actually forces the material to go through the die. So it is all together a different geometry for the gear pump extruders or planetary gear extruders I am not going into the details. Let us fix up our attention here for the time being.



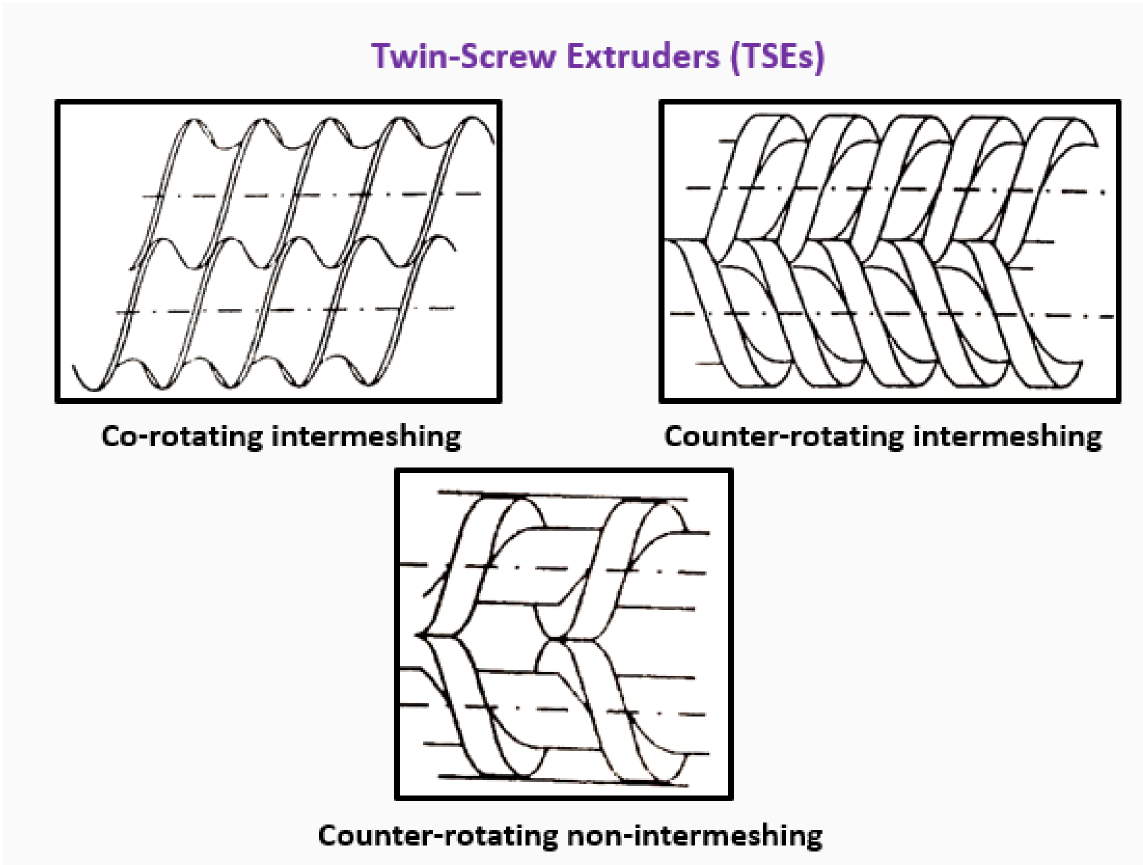
So basic features of extruders conventional single screw extruders the for thermoplastic processing are available in various size I mean 20 to 600 millimeter diameter you can represent it inch also based on the convention and L by D ratio like 20 to 30 with 24 being very common. So the mass flow range also you can see this is the output rate. We will try to look into that how you calculate the volumetric flow rate with the die without the die. So vented screw design again it is a typical design. See you are trying to take it through the feed to the compression zone.

Now imagine the situation if you have some volatile it will try to come out of it. So what it is done suppose you have a some right handed screw design just keep it discontinuous and make it little bit you know opposite to that and then followed. So what will happen whatever pressurize that pressure will be releasing between that juncture okay and you have a little bit small vacuum you generate. So whatever, and then again, you go for a little bit of compaction of the mass. So that is how venting is being done.

So special purpose extruders and when you anticipate in your mass of the polymer or polymer compounds you have quite possibility of generation of some of the volatiles. So think about the situation you are feeding a granules. Granules are getting compacted in between the granules you have air and that air is getting compacted still some of part of it is dissolving in the molten polymer mass eventually and if it remains think about once it comes out of it the pockets will expand. So you have defects all around there. So L by D range can be 35 to 45 although I was talking about there for high volatile containing system twin screw extruders are best suited for de-volatilization okay.

So in that case your compaction and squeezing out the air okay is more okay. Think about when you are we are talking about rubber okay. In rubber when you mix it in a internal mixture okay rubber try to penetrate in between the air pockets but still it may not be fully squeezed out even though you anticipate everything squeezed out but still there should be some volatiles in between. So it depends on what type of a ingredients you have. During mixing have you are there any chances of generation of low molecular weight some low volatiles small amount.

Remember you are dealing with many ingredients which can decompose okay. So nonetheless although you use it as per the thermal stability but there are always some possibilities. Rubber extruder is typical as I mentioned L by D ratio is quite smaller as compared to the you know plastic extruder reason I told you because longer the extruder will be viscous heat generation will be more and scorching as well as degradation will be problematic. So there are two types of extruders in general one is called cold fit where L by D ratio is quite high longer 15 to again 20 okay. So why cold fit you are feeding the rubber premix in a cold condition itself during going through the screw and barrel that friction it generates it gets heated up.

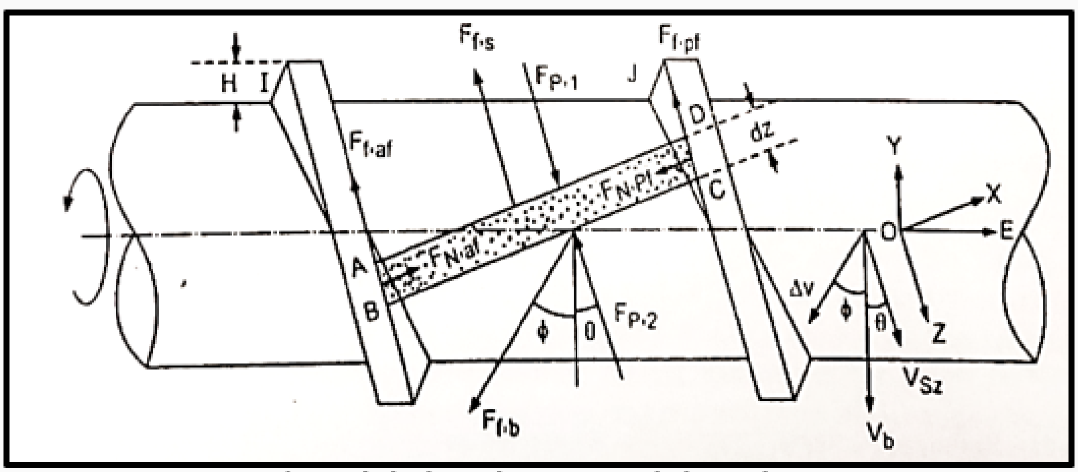


But while the other one you do not need that that long L by D ratio because you have tried to feed it in the warm condition you have a warm up meal. In the meal you are trying to after your I mean suppose if one day before you mixed it okay you take it out you have to warm it up in a meal several times milling it will get heated up in the warm condition you should have a separate feed system that will feed to the hopper of that. So there will be different all together feeding system available for the hot feed extruders okay. So in general this is a kind of a geometry you can see as from this cartoon you can see there is channel is more or less I mean this clearance is more or less same I mean this top to bottom barrel and screw but you see this slight pitch is diminishing. So it is getting compacted once its passages from feed to the other end just typically show you this thing.

So group barrel extruders you see why you want group barrel this barrel is flat here no so if you have a group think about what will happen it will have a additional friction. Additional friction will happen and why rubber conveys where polymer conveys there should be a differential addition between of rubber or polymer with the screw with the barrel. So if you do not have a difference of addition so the rubber or polymer will not flow through basically okay. So in order to have it first of all you have to make a difference even if these two materials are same the roughness you have to manipulate or else you have to manipulate on the temperature so that you generate between the extruder and barrel you generate the differential addition. So that is one of the one but in this case group barrel is you are intentionally having some groups okay and it works well for high molecular weight high viscosity polymers typically with the low friction coefficient of friction.

So like olefins like polystyrenes particularly plastics ABS sand okay so in that case it will adhere well with the barrel okay. So that is the thing but it again demands high power consumption that is the another bottle neck of it okay. So this is the schematic of a typical grouped feed section part of it okay. So I am not going into the details but it looks typically of this sort. So there are turbo cool foam extruders available you see this turbo cool screw design actually okay.

MATERIAL FLOW THROUGH SINGLE SCREW EXTRUDERS



Forces acting on the solid plug element and the velocity components

So a screw flight design based upon the series of new flight geometry so you have additional screw flights there which promotes the cross channel flow. As I told you not only that there is one type of a extruder available particularly for rubber in order to facilitate the radial mixing you have pin and barrel design. So your barrel has certain holes some staggered pins are inserted remember it should not you know touch your screw while rewarming but at the same time it will generate some sort of a pin in a staggered way that gives you kind of a cross flow. So radially also it will be uniform axially okay it is going in this direction of flow but radially also it takes care of that extra mixing action you can get it. So efficient mixing and heat transfer is the reason here okay.

So now if you look it at the several components of it an extruder single screw extruder that is hot off at rubber industries for the extrusion okay starting from the I mean drive motor to the reduction here that is very common in total mill or so you have a motor has certain rpm so you have to have a reduction here okay. And then it finally transmit the force okay through a cam or some mechanism to the shaft to the screw itself okay and screw rotates by that process the barrel screw screen breaker this three elaborate separately screen breaker plate and die okay. So this plate part I will take it separately in the so what is happening from here to here in during the journey of a say let us say a plastic material it is slowly melting as you can see from transition 1, 2, 3, 4 and finally by that time 5 and 6 zones are obtained you have a fully molten plastic which is coming out through the die here okay. So that you must understand that let us try to quickly look it into what is the principle how the polymer flows from one point to the other number 1. Number 2 what is its relevance to the rheology at least pressure volume relationship volumetric flow rate with the head pressure delta p and across different temperature ranges okay.

So let us try to concentrate here little bit more okay. This is a typical drawing that will make you understand what the flight means, what pitch means, what are different you know helical angle that your screw is making okay and that you must understand from here. So as the material moves ahead it is pressed more tightly against the one flight flank known as the active flight flank okay. I am just reading out okay or the pushing side then the other the positive flank resulting in the pressure gradient along the width of it okay along the width of it you generate a pressure difference which causes the melt to circulate and give a mixing effect okay. And the rotation of the screw makes the material move along the channel so what is happening it is not material going it is an ramp it is a directly it is going but a screw through the channel it is messaging.

$$F_{f,b} \cos(\theta + \phi) = (F_{f,s} + F_{f,af} + F_{f,pf}) + (F_{P,2} - F_{P,1}),$$

Where θ is the flight angle and ϕ is the angle made by force $F_{f.b}$, with plane normal to the screw axis.

One can neglect the pressure difference term

$$F_{f,b} \cos(\theta + \phi) = (F_{f,s} + F_{f,af} + F_{f,pf}) = F_s \text{ (say)},$$

Where F_s is the total frictional force acting on the solid plug due to the screw surface.

The ratio of two frictional forces

$$R_f = \frac{F_s}{F_{f,b}} = \cos(\theta + \phi)$$

For the material to move forward, $F_{f.b} > F_s$, or the barrel surface must be made rough and that of screw be made very smooth.

The expression for velocity of plug

$$v_{s,z} = V_b \frac{\sin\phi}{\sin(\theta+\phi)}$$

where, V_b , is the barrel velocity corresponding to the screw rotation of N rpm i.e.,

$$V_b = \pi D N$$

and D is the barrel diameter.

So ultimately considering the geometry of it I mean say for example, I mean pitch of the flight its width of the flight excluding that you can calculate the volume element in each flight if you know the rpm per unit time how much it is going in that direction component to the x axis if it is a x axis so you will be able to calculate volumetric flow rate that way. Remember what I am talking about up to now I am considering there is no die or there is no resistance it is a open discharge okay. So that way you must be able to calculate yourself I will give you a problem there in the tutorial related to volumetric flow basically where you can calculate given a geometry there I will explain you each and every component of an extruder starting ground screw to barrel to flight depth pitch okay flight angle etcetera etcetera this is the diameter of the barrel so. So the root diameter of that typical plasticizing screw varies along the length smaller in the solid conveying zone to provide deeper channel so two things see if you make the channel depth that means the clearance between the barrel to the root of the you know screw so you are generating more volume or else your pitch length between the two successive screws one revolution how much it goes basically that is what is the pitch. So that way either is the which side of it or it is height side of it it actually amounts to the volume.

The volumetric flow rate of the solids, Q_s, is given as

$$Q_s = HWv_{s,z} = \pi^2 D(D-H)\,H\,N\left[\frac{\tan\theta}{1+\dfrac{\tan\theta}{\tan\phi}}\right]$$

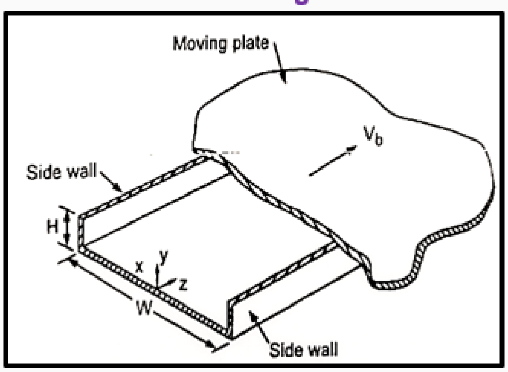
where H is the flight height or the channel depth and W is the channel width.

So that way you here you can see here from here to here you see there is gradual initial in the fluid zone is more open you are putting in more and more material and something maybe you know not full filled that is what the question of air pockets are coming there then gradually gradually this depth is diminishing till to the tip of that I mean where it comes to the close to the die zone. So you can see that that way it is getting compacted. So of course after the compressor zone significantly over you need to have a metering zone I mean no more compaction it should be a laminar flow and here pump sits over there if you have not enough pressure generated then your gear gives the extra pumping action to extrude in that is altogether different story but it has a relevance since I told you few minutes back. So it progressively increases to facilitate compression and higher melt pressure so it generates a melt pressure del P pressure drop which is talked about. Now try to take the another part of it which is a workhorse of plastic industries is a twin screw extruder as the name implies the assembly of two same size screw housed side by side in the same barrel in the shape of a horizontal 8 the screw rotate with the same speed inside the barrel that is the basics of it although it can be co rotating it can be counter rotating inter machine or counter rotating non inter machine I already talked about inter machine means the radius of so there is more nip action when high intensity mixing action.

So the twin screw extruders are increasingly used in variety of wide ranging application for example mixing, blending, compounding of thermoplastic polymers, ravers with different ingredients profile extrusion also after that the mixing is over and then you have a metering zone and then you have a final die zone. So you have extrusion thermally sensitive material like PVC, speciality, polymer processing, de-volatile lysation, reactive extrusion. So advantages of twin screw extruder over SSE more mixing action so that apparently you do not need for rubber that part you are taking care in the internal mixture or Banbury itself for plastics you are making it happening in one go. So that is why single screw extruder is quite common in rubber industries while twin screw extruders are common in plastic industries. Higher rates of mass and heat transfer giving uniform obviously you have a screw inside the screw you have a cooling part of it no risk of degradation so if you have a temperature control more degradation but again can I do it with the rubber that much temperature control is not sufficient enough for rubber otherwise all the internal mixture would have ban is by now.

So it can process powder slippery material the capital cost of TAC is all automated so feed to you know after extrusion pelletizing bagging everything can be you know automated quite quite automated. So you must visit a plastic industry specially polyethylene or PVC even how twin screw extruder is effectively used you must visit as a learner there. So if you compare a co-rotating again counter rotating when co-rotating when counter rotating both screws rotating in clockwise manner that is the definition another is one clockwise another anti-clockwise. So in co-rotating maximum transverse velocity is always at the tip of the two screws but in this case transverse velocity occurs in the intermeshing region that is the difference. So you can immediately foresee that more mixing action.

Flow in Metering Section



The velocity of the plate corresponds to the peripheral velocity at the tip of screw flight

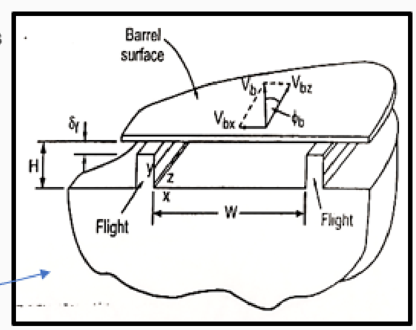
$$V_b = \pi DN$$

In the channel or Z-direction, the down channel velocity, as

Forward movement of the melt $v_{b,z}(y) = V_b \cos \theta,$

In the transverse or X-direction, the cross channel velocity, as

Melt circulate within channel $v_{b,x}(y) = V_b \sin \theta$



Parallel plate model of flow in metering section of a SSE

So during each rotation of the co-rotating screw most of the fluid is in one loop in is transformed to the other loop giving a better mixing behavior which is not the case for counter rotating but obviously for intermeshing case you have you have more sort of intense nip action that that you must understand although the transfer is is the is out is is out that another type of a mixing mechanism. Magnitude of axial velocity is higher which gives higher throughput because it is going to going more towards forward side in other case low throughput although you have a transverse velocity is high and axial velocity is negative giving a reverse flow those are the things you must understand. So if I plot L by D ratio with the del p one interesting thing if you increase the L by D ratio the pressure drop finally with pressure you are trying to extrude it out the head the critical pressure it is generating that is getting pacified more and more if you have increased L by D ratio. So that is one part of it with the both psi as well as mega Pascal unit is depicted here approximately how it changes with the head pressure with the L by D ratio. It is all about the head pressure before extrusion mind that.

Now as I mentioned it to you these three items are very important and in fact indeed the eighth lecture onwards I will take you through only concentrating that zone also die lip and die zone. So I will not consider the screw zone that has a more complication as you understood now even I am going to show you it is going to be even more complicated within a while. So what you have is clean see whatever you are getting out of it there is no guarantee there is no agglomerate un-molten polymers pigments. So you need to have a screen just stain it it is like a stainer. In fact in rubber mixing also for highly dispersive mixing and all you can use it with a you know kind of a two roll system having differential speed that kind of a geometry.

But still if you can foresee sort of a you know agglomerate you have to extrude it and having a skin pack and to stain it simply otherwise your product will not be that lucrative in terms of finish. So this kind of a depending on your requirement different message screen screens are available and then just before entering the die zone I mean die land and die lip. Then you have a breaker plate that is very very important. So it is a thick metallic disc having a large number of you know countersunk holds parallel to the screw axis preventing the stagnation of the melt. As I mentioned if you recall the stagnation will give you additional defects.

Well talking about some part of it I talked about that. To support the screen pack to prevent it from buckling so breaker plate has that job also support you have to have a support otherwise just simply putting screen pack and you have a flow will bend simply bend. So it is a support also after that and then the smooth output of the spiraling melt so causes due to the rotation of the screw. So those are the things so you are giving a check there. Have you visited some dam so is as if like a one of those checkpoints.

Extrusion die is one of the major component and most of our you know analysis in the eighth lecture will be solely based upon this. See there are there is a phenomena called die zone I already talked about there is a phenomena called you know change in surface texture of it. So and sorry I forgot one thing I was talking about mixing in a two roll mill is called refiner mill. So refiner mills are very dwarf mill and having very high friction ratio to have to make the get the agglomerate broken and before you process it for extrusion you have to have another extrusion small extrusion with the strainer that stands out basically even if you have some leftover agglomerate aggregates there or pigments. Anyway coming back to the die again I mean I hope you understood the screen pack as well as breaker plate.

Now immediately that the die will be mounted at the end. So this is what is extrusion die. Many a times people do it in an iterative way makes a die see what is what is see this is a typical example you want a product shape of like that if your die shape is like that only you end up have a deform sort of a thing. Rather if you have a die shape like this only taking into consideration the die shape because wherever you will be more strain soil is going to be more. So any corner the soil is going to be more. So that way if you want to have a this shape finally you want to have a die shape like this.

So these are the some of the thumb rules but we will try to show you in a fluid mechanical way by computer simulation way both in a forward extrusion and inverse extrusion which is hypothetical but it will make sense when I will be depicting you. So how to come with a perfected die in both cases that is what is the major part what I am going to teach you for the little bit in the intermediate stage. And as I told you as I promised you if time permits or over the years if I feel so we can we can go into the the detailed design of a extruder may be detailed design of a mold detailed design of a both injection as well as compression and transform mold. So then it will be you will be useful to the industries in particular. So extruder a simple shape is a say tube shape circular shape you do not have any problem only thing is the diameter may change but you do not have a geometrical deformities that way.

But you have some more you know complicated shape then then then those questions arises if you have a fiber field like I mentioned it to you fibers can protrude out during extrusion. So the ideal requirement should be while designing the die balance the mail flow by providing more uniform exit velocity that I told you several times exit velocity there should not be any sort of eddies form many times I told you while talking about simply capillary geometry I talked about those and those corrections also if you recall. Then achieve this flow balance with a minimum pressure drop through the die I will explain you and steam line the flow to avoid abrupt changes of flow passages these are very very important thing and the pseudo plastic nature causes the velocity to be highly shear sensitive that I told you and the viscera city gives you stress relaxation or normal force differences that will be manifested in the form of a die square. So I will again come back I mean so what we considered here see die land inside the die before the die there is a entry also and after it extrudes out it takes some time to have a equilibrium you know sort of a you remember I was talking about the running die sure that means right at the point when it exists the die. So these are the some of the considerations what should be the shape of the die and that particular shape of the die will giving rise to a shape of the final product.

So those things will be taken care of in the eighth lecture but in a computational way. So what I am to try to give you some more sense so that you better realize well I will be dealing with those. So material flow in a single screw extruder again we have tried to take a solid plug element here across within that what are all forces acting and what are all geometrical factor you have to take it into consideration while designing. So the plug is dragged along the channel which is you know an wound after cutting it to ij by a infinite plate representing the rotating barrel. So this is a hypothetical plate and then the screw is stationary we are trying to you know do it other way round this analysis screw is stationary a barrel is moving is a vice versa way.

The solid fills the channels completely it is a plug flow channel depth is constant I am not taking into consideration all this feed zone compression zone metering zone that again adds the complication here. So you can understand now how complicated it is we are trying to make it simplified coefficient of friction is independent of pressure. What I try to talk about two friction coefficient one with the you know barrel another with the screw. So that both of them I am assuming it is independent of pressure that means in the root or in the feed zone or whatever initial thing at the top where the pressure is gradually increasing I assume it is not changing correct. And then the effects of gravitational force centrifugal force changes in the density of the solid is negligible.

✓ **The extruder output Q, thus, consists of three components, namely**

(1) Drag flow, Q_D

(2) Pressure flow, Q_P

(3) The leakage flow Q_L.

$$Q = Q_D - Q_P - Q_L$$

The velocity distribution in Z-direction is

$$v_{b,z} = V_b \cos\theta = \left(\frac{H^2}{2\mu}\right)\left(\frac{dp}{dz}\right)\left[\left(\frac{y}{H}\right)^2 - \frac{y}{H}\right] + \frac{V_b y}{H}$$

The cross channel velocity distribution is given as

$$v_x = V_b \sin\theta = -\frac{2y v_{b,x}}{H} + \frac{3y^2 v_{b,x}}{H^2}$$

The volumetric flow rate, Q is given as (leakage flow neglected)

The ratio of $$\frac{Q_P}{Q_D} = -\frac{H^2}{6\mu\, v_{b,z}}\left(\frac{dp}{dz}\right)$$

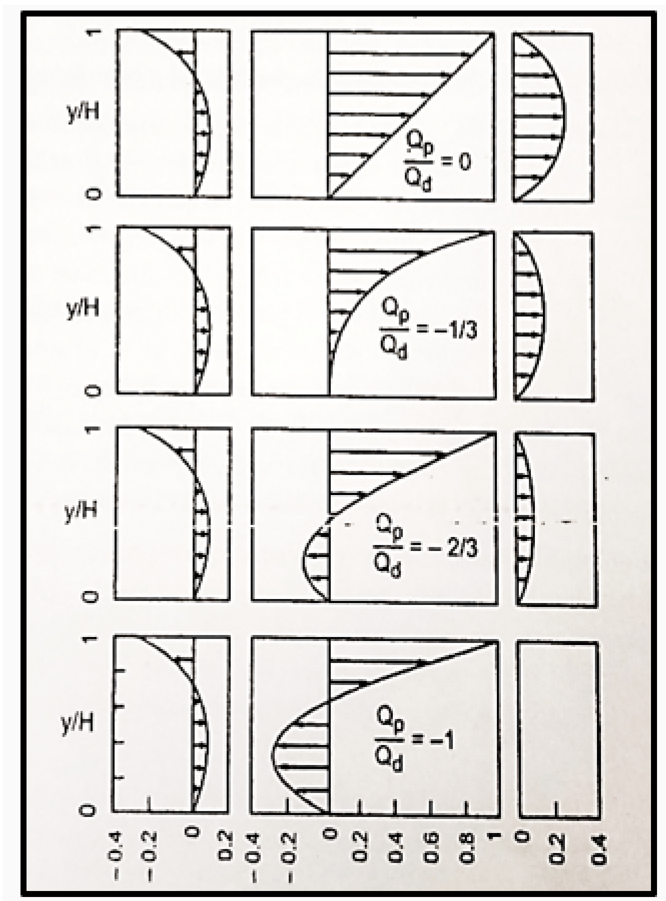
$$Q = (Q_D - Q_P) = \frac{v_{b,z} WH}{2} - \frac{WH^3}{12\mu}\left(\frac{dp}{dz}\right)$$

So with that simplification the force suggest if you do the force analysis writing a free body diagram here you can see what are all force responsible frictional force between a solid and screw at its root its active flight crank and its passive flight. Then second thing frictional force between solid and the barrel surface. The third one is the net pressure force acting on the normal to the plug surface this is the plug surface remember. And the direction of the channel so this two force difference basically and the normal force acting on the solid barrel perpendicular the channel direction. So remember it is undergoing this kind of a circular flow so obviously there will be another component theta of that or with that depending on the helical angle you can always anticipate.

So likewise I am not going into the detail force analysis but bottom line is that as I mentioned it to you if Fb should be greater than Fs between the barrel and the surface of the screw there should be a differential friction. See one question is given for you do not worry about the question. Now question is very simple you can answer it from the common sense. See why screws are polished or chrome or nickel plated and the barrel have rough surface finish and even grouped one of the example I talked about group depending on the nature of the material.

Otherwise what will happen screw will rotate nothing will flow. So this force difference must be there this is necessary and sufficient condition a material to convey from one end to the other correct. So you can obviously remember we have talked about the barrel velocity you may be wondering barrel is not moving screw is moving yes. So but we made it other way round hypothesis. So if you try to calculate barrel velocity very easily if you know the barrel diameter and rpm of the screw you can very easily calculate out the velocity from there.

Of course the component forces also you can calculate. But what is important for us one end we are feeding other end we are taking out. So what are the variables we have we have certain variables like flight height channel depth channel width and of course the helical angle. So considering that what is the volumetric flow rate we can calculate out considering the geometry to account. And considering if phi equals to 0 f s those two forces equals to f b into cos theta indicating two frictional forces are equal in magnitude and act in the direction opposite to that.



Thus the material will not advance but keep on circulating correct. So that is not the case but phi the maximum solute conveying takes place with the expression right side above the equation when tan phi tends to 0 or an angle phi tends to 90 degree. So from this equation you can easily get those solutions. So accordingly you have to have a flight design. So flow in melting is a and delay sections this state of the material in the melting section of a single screw again once again you can see frame by frame the analysis of it. So I am not going into the details neither I just want you to have a mental map that is how the circulatory motion is happening and what are the gradually changes gradual changes in between two flight it is happening you anticipate that.

Flow in the metering section as I mentioned it to you is utmost important because I will not consider what happened there what I am anticipating whatever turbulence eddies we have we get rid of we have done sufficient radial and those mixing component of it. Material is relaxed because if it is elastic things we have to give a sufficient space so that it relaxes kind of torture it underwent before like compression and other zones and then it is ready to be extruded now we generated sufficient pressure. So simple plate model of drag induced a pressurization of the fluid flow through a rectangular channel having a large aspect ratio and the velocity of the plate corresponds to the you know peripheral velocity at the tip of the flight we can calculate out VB equals to pi dn and of course, so in the forward movement you can calculate and for the circulatory movement you can calculate out the components of it quite easily. But ultimately what I am interested in is a volumetric throughput and it depends upon three types of volumetric flow one is a drag flow which I told you because of the frictional difference of it or additional difference you can anticipate second is pressure flow because remember from the feet to the die exit zone pressure is maximum at the die head so there will be opposite pressure flow and of course, the leakage flow. So if you just subtract pressure and leakage flow from the drag flow component you are getting out you will be able to calculate the resultant flow that discharges in open discharge conditions we are remember we have not assume any sort of a constraints while flow here.

Effect of the Clearance

$$Q = (Q_D - Q_P) = \frac{v_{b,z} W(H - \delta_f)}{2} - \frac{WH^3}{12\mu}\left(\frac{dp}{dz}\right)(1 + f_L)$$

So again I am not going without going into the geometries you can pretty well you know correlate or interrelate pressure volumetric flow rate with the geometries of course, the viscosity of the material here is taken into consideration as nu here it can be eta also. So this we have used it interchangeably everywhere. So you can consider the volumetric flow rate of course, what is important just assuming leakage is negligible we designed clearance flat clearance in such a way what is important Qp by Qd pressure flow by drag flow drag flow is a forward flow pressure flow is a backward flow. So this actually gives you a velocity profiles where cross channel flow in the back flow direction as well as in the forward flow direction with the resistance without the resistance. Resistance means here in the first case there is open discharge and you see in the first case this is the so one interesting thing in the cross flow this however, it is close discharge or open discharge does not really make much of a difference.

But on the contrary if you look it at this type of a flow as I am increasing Q by d ratio from top to bottom that means, first case Q by d is 0 Qp by b is Qp is 0 that means, it is always a forward open discharge condition. So gradually I am giving the constraint more and more that means, at the end this is the extreme condition when I simply blocked it. So in this case you see backward flow is gradually increasing back flow is increasing. On the contrary if you consider the forward flow axial flow. So in that case you see is a full developed parabola and that velocity is diminishing and it will diminish as obvious when there is a perfectly closed sort of a situation.

But remember one thing two condition y equals to 0 yy h equals to 0 and one these two conditions yy h in first cases main flow is always positive being 0 at y equals to 0 maximum at y equals to h so that you have to consider. Now before we end today's discussion on extrusion. another part is also important what is the effect of clearance, clearance means clearance between the flight screw and the barrel. So you can easily derive Qd minus Qp which is a resultant flow remember I am also considering leakage flow to be minimal. So with that you can have such a kind of a relationship with the channel depth I mean channel depth in the drag flow and different conditions.

But what is the important for designing an extruder the die which you are using and screw you are using there should be a combination. So what you plot polymetric output versus extruder head pressure. Say for example I have a shallow channel screw and I have a large die orifice. So I have to really see the interception of that and that is the critical volumetric flow rate I will be obtaining.

So these are some of the diagrams which are very very important. Second diagram you can see volumetric flow rate here as a typical 90 mm screw feed extruder with different screw speeds you can see different 80, 60, 40, 20 rpm. And then you see volumetric output with the pressure drop of course at two different temperature line you can see one is the temperature of the die head and there is a temperature of the melt itself. So you can figure out the condition where you get a optimum throughput. So these are the some of the nomograms are often used but today it becomes highly computational fluid mechanics based and that I will try to highlight. But I told you at the end these are the some of the stories you must quickly before we conclude you can always compare I mean whatever problem you get it in a extruder you can divide it into two machine related problem and material related problem because I am assuming rest of the part is well taken care of because it is a you know simply robust machines otherwise the machine problem can be pretty much unless otherwise the slacking of the belt wet air regular maintenance stuff.

And one problem always wherever you see a regular pattern of defect you have to check your screen pack some stagnation or what ok. If you have seen some porosity blister if you have some filler it has some moisture content try to see it if it can cannot be circumvented with yours too then you must need a vented screw or you know pin and barrel combination. So there can be some problem with the operators also but it is quite less as I mentioned most of the machines are automatic these days. Weigh main problem should not be there and feeding an extrusion dimension adjustment it it used to be for a you know fully a manual one ok.

So some of the defects are shown center blast piping surface cracking. So these are the some of the common defects with the temperature with combination of the screw design as I mentioned it even though the die design you can take care of it. So without going into the details much with the more complicated you know combination of extrusions this can be understood much more. But it is again a preliminary introduction to it again well I will stick to the same book what I talked about earlier understanding rheology and technology of polymer extrusion by Batchupulas is a very very authentic book you can always refer to. Again I hope I could give you some preliminary idea about the extrusion without considering much of a mathematics of it much part of it but the basics of it stick to the basics I will take you to the basic of design also particularly I will concentrate on the die in the upcoming eighth lecture basically. Next class I am going to highlight upon touch upon the injection basic process of injection from the processing point of view a little bit on the basics of flow characteristics of the material and thank you.