Lecture 33 – Extrusion

Welcome to the next segment of extrusion under the areas of polymer process engineering. Hello friends, we are going to start another segment that is called the extrusion which is for polymer processing. Now, before we go into the details, let us have a brief outlook on what we discussed in the previous chapter. We discussed the different materials used for the injection molding process. If you recall we discussed the injection molding process in two different lectures and we discussed how important is the material selection. So, we discussed this different material being used for the injection molding and the thermoplastic, thermoset, elastomers, and all those things.

And the different fundamentals, we had a brief outlook like crystallinity, amorphousness, semi-crystalline behavior, molecular weight and distribution, then viscosity, density, and viscoelastic behavior, including Newtonian and non-Newtonian. Then we discussed the effect of temperature on polymer behavior. And lastly, we discussed the orientation. Now, in this particular chapter, we are going to discuss another polymer processing operation and that is called the extrusion.

Now, extrusion is again a very important process of polymer processing to produce the desired parts, particles, and other utility or commodity products. We will discuss the different extrusion aspects like a single screw and the zones or regimes in the extrusion process, solid conveying or feed zones, then the transition and plasticizing zones we will go into discuss, then the melt and metering zones. We will discuss the geometrical aspect of extruders. It is quite essential to have a look at this one because it also plays a vital role in deciding the fate of a product. After this, we will discuss the twin screw extrusion. Now, in the polymer processing operation, there is involvement of a flow, deformation, and the transfer of energy.

Extrusion

❖ **Single screw**

✓ The polymeric material is fed into the hopper and then to the screw channel.

✓ The screw, driven by a motor through a gear reducer, rotates in a hardened barrel.

✓ A thrust bearing absorbs the rearward thrust of the screw.

✓ Thermal energy is supplied by the internal heat generation of flowing polymer and external heaters or both.

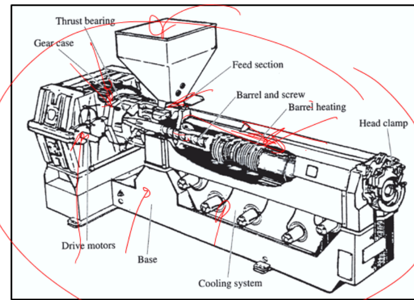


Figure: Showing screw extrusion

Richard G. Griskey, Polymer Process Engineering:, First edition, Springer Science Business Media Dordrecht., (1995), ISBN: 978-94-011-0581-1. 9

The goal of polymer processing operation produce a usable object, a useful product, it may be commodity plastic, maybe engineer plastic, or it may be highly specialized parts. So, for all polymer processing operations, various necessary parameters like flow or deformation or both, means you must know the rheology aspect. Then the transfer of heat, means you need to be acquainted with the thermal behavior, how this polymer behaves when you apply the heat or when you apply the cooling, then is there any deformation, so all these things you need to address. Then the mass transfer, basically it is useful for producing the foams. Then the chemical reaction, that is especially the reaction injection molding.

The other important aspect of polymer processing is changes in the polymer structure, such as crystallinity as well as orientation. We discuss this one in the previous segment. Such types of changes have a direct influence on polymers and properties like mechanical and electrical properties. So, all polymer processing operations can be characterized in 3 segments. One is batch, semi-continuous, and the continuous.

Now here is the classification of polymer processing. Like in batch, we may have a casting, we may have a compression molding, we may have a sheet forming, thermoforming, transfer molding, all these things we are going to discuss. In the semi-continuous mode, the blow molding, the injection molding, or the rotational molding, then continuous, this is the calendaring, extrusion, pultrusion, fiber spinning, all these things. So, these are the various polymer processing operations. So, for ease of study, we divided all these things into 3 segments, batch-wise, semi-continuous, and continuous.

So, let us start with the extrusion. This can be defined as the act of shaping a material by forcing it through a die. So, the devices used for the polymer processing to carry out extrusion, are known as extruders. So, extrusion is a process and the extruder is the machine. Now, such types of devices are pulse-free pumps, which are capable of delivering thermally homogeneous polymer melt at a uniformly high rate.

Now, the extruder is an important part of for operation using dies as well as in which a melt is injected into a mold-like injection molding. Now, the extruder is the helical screw pump, which converts the solid polymer particle into a melt that is to be delivered to a die. So, first thing the conversion to a melt, and then it is forcefully delivered to a particular die. Now, the screw extruder because the extruder is the main component, can be classified as a single screw and a twin screw. Now, let us talk about the single screw.

This is the typical you see the screw extrusion. The polymeric material as usual is fed into the hopper here and to the screw channel like this. Now, the screw is usually driven by a motor through a gear reducer that rotates and hardens the barrel. Now, this is the barrel and this is the barrel heating zone and this is the feeding section and you see this is the gear case and this is a dry motor that runs the things and here we may have a cooling section with a base. Now, a thrust bearing, this is the thrust bearing absorbs and the rear wants the thrust to the screw.

The thermal energy is supplied by the internal heat generation like here of flowing polymers and external heaters or sometimes both. In some cases, external cooling is also needed when internal heat becomes so great because you see the frictional heat is again very crucial, it also adds to the material. So, whenever the heat goes on, then you need to have some external cooling. So, that is why there is a cooling system. The plastic granules are melted as they are conveyed and forced through a breaker and a plate screw combination ultimately to a die.

Sometimes a backflow valve is positioned between the breaker plates and the adapter to control the process. Now, there are 3 zones or regimes in the extruder, one is the solid conveying or feed zone, the second is the transition or plasticating zone and the third one is the melt or metering zone. So, if we plot, then you see that this is the melt and a solid polymer, this is the solid zone, this is the plasticizing zone, then this is the metering zone and here you see that this is a die end. Now, in the solid conveying or feed zone, the pallets are conveyed into the main segment of the extruder if you recall the figure of the extruder the conveying capacity is equal to the extruder's melting and pumping capacity. So, the theoretical approach is not well defined for this particular zone.

Extrusion

There are three zones or regimes in the extruder

1. Solids-conveying or feed zone
2. Transition or plasticating zone
3. Melt or metering zone

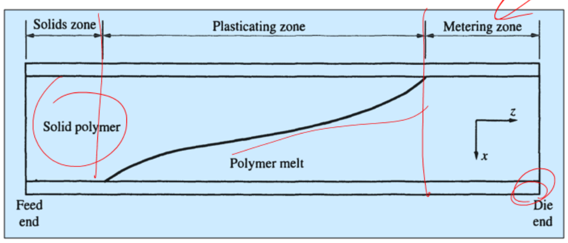


Figure: showing three zones or regimes in the extruder

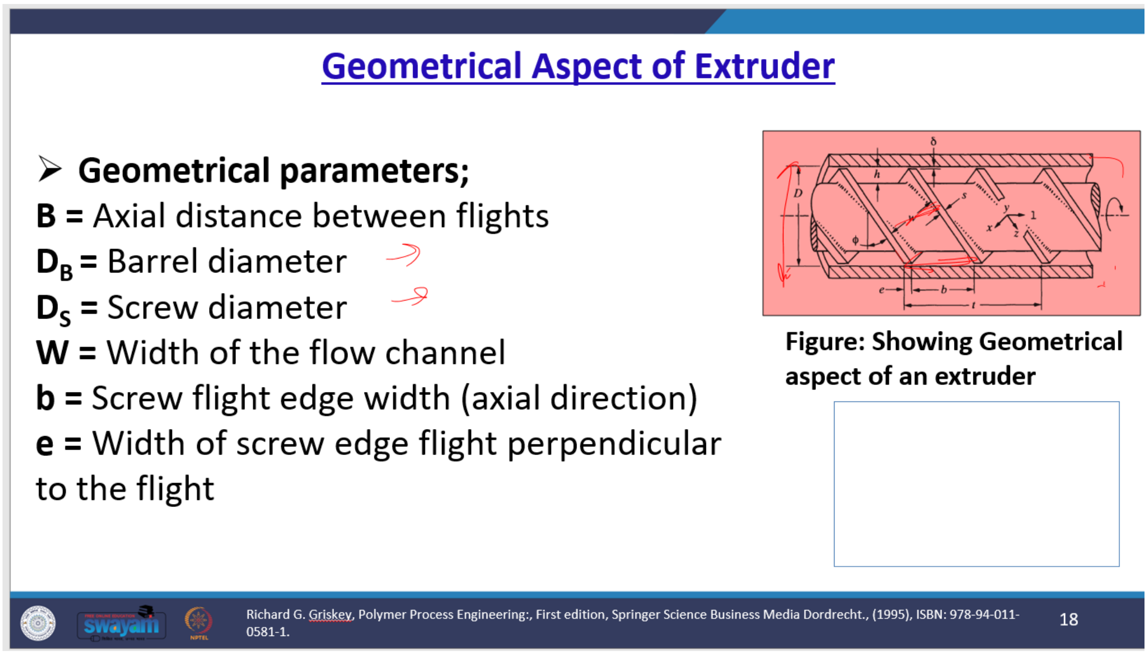
Now, the semi-empirical approach is used that considers the pallet to behave as a solid plug. Now, the plug behavior with little deformation and the rate of movement depends on both the back pressure and the frictional forces on a screw flight and barrel. Now, the frictional forces because frictional forces also impart a crucial role, add on heat. So, the frictional force is a function of a screw geometry and the nature of the extruder surface. So, the rough surface may create more frictional force and thereby impartion of more and more heat.

The helix angle is the critical factor. Now, let us talk about the plasticating zone or a transition zone. It connects the feed, this is the feed and this is the metering zone. It connects the feed and metering zone. The length of this zone varies with the type of material being used.

The cross-section of the flow channel is reduced in this particular zone. So like this. For the rubbery material, the pitch angle is changed so that the overworking can be avoided. For the plasticating zone treatment, this requires the analysis that combines the flow, the heat transfer, and the mixing. Mixing is again very important because the granules are there, sometimes you need to add some dyes and other things.

So, the mixing and heat transfer because you are heating as well as the frictional heat is also being generated. So, you need to augment all that heat and you need to maintain a proper temperature. Now, a usable approach must be established to build effective procedures which means optimization is quite essential. Let us talk about the melt or metering zone. In the metering zone, the material is in the melt form.

That is why the glass transition temperature and melting temperature, the knowledge about these two temperature is quite essential. The treatment combines flow and heat transfer. Now, while the metering area is still complex, it lends itself to the technique of the technical examination more readily than the other two zones. Now, it is appropriate to take into account the numerous significant aspect of screw extruder geometry before beginning the technical study at each of the zone. Now, let us discuss the geometrical aspect of the extruder.



Now, here before we start to discuss the various geometrical parameters, this geometry plays a very vital role not only in the mixing but also in the heat segment and the further movement of the polymeric material. So there are various geometrical parameters associated with this particular study. One is the axial distance between the flights like this. These are the flights, so you need to know about the axial distance between the flights. Then you must know about the barrel diameter, what is the diameter of the barrel.

Then screw diameter, what is the screw diameter you need to know, and that is referred to as ds and db in the usual notations. Then w is the width of the flow channel, you must be aware of this w aspect. Then screw the flight edge with the axial direction and width of the screw edge flight perpendicular to the flight. So, all these parameters you must know. Apart from this, you should know about say h which is the barrel diameter and screw diameter, the difference between the barrel diameter and screw diameter.

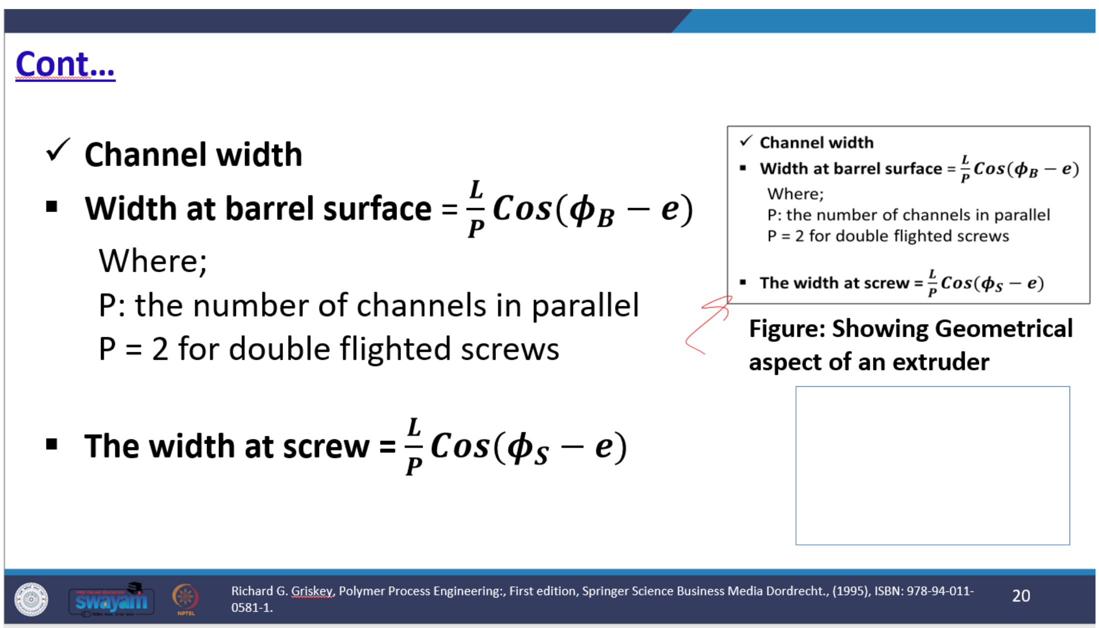
Then screw the flight edge width that is referred to as s. Then this is again very important and you should know about this one before deciding things. And clearance between the screw flight edge and the barrel should be needed because this is essential for the free movement of the polymer towards the forward direction. So, this is referred to as the delta. The helix angle is psi, this is the helix angle.

So, this is again very important to know. The channel width, the channel width usually this is the width at a barrel surface, and referred to as

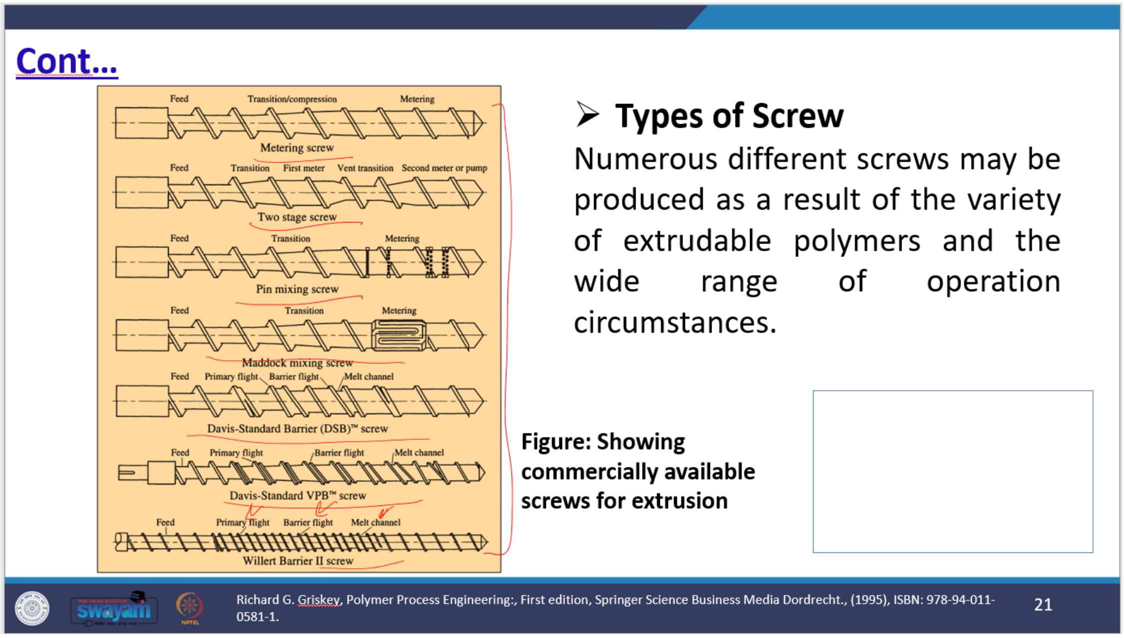
Width at barrel surface = $\frac{L}{P}\cos(\phi_B - e)$

Width at screw = $\frac{L}{P}Cos(\phi_S - e)$

where P is the number of channels in parallel and P is equal to 2 for double flight screw and the width screw is L by P cos phi s minus e. This reflects the geometrical aspect of this extruder. Now here are the numerous different screws, they may be produced as a result of a variety of extrudate polymers and a wide range of operation circumstances. Here you see that the commercially available screws like you see that metering screw, two-stage screw, and pin mixing screw, you see the difference in the shape.



Then Madoc mixing screw, Davis standard barrier screw, Davis standard screw, Willard barrier screw, all these things you see that different the prime flight, barrier flight, melt channel. So all these are the differences you can easily analyze that there is a difference and this all depends on the processing condition, it all depends on the polymers being used for the process in question. Now there is again a crucial aspect is that typical pressure ranges for the dye because ultimately the melted polymer will flow through the dye. Now to convey the polymer through an extruder, ultimately it should have to pass through a dye. So, usually, there are different types of a product and enlist the pressures like cast film they must have.



1.4 to 10.4 mega Pascal, then sheet 1.5 to 10.4, then a pipe's usual process for producing pipe is the extruder.

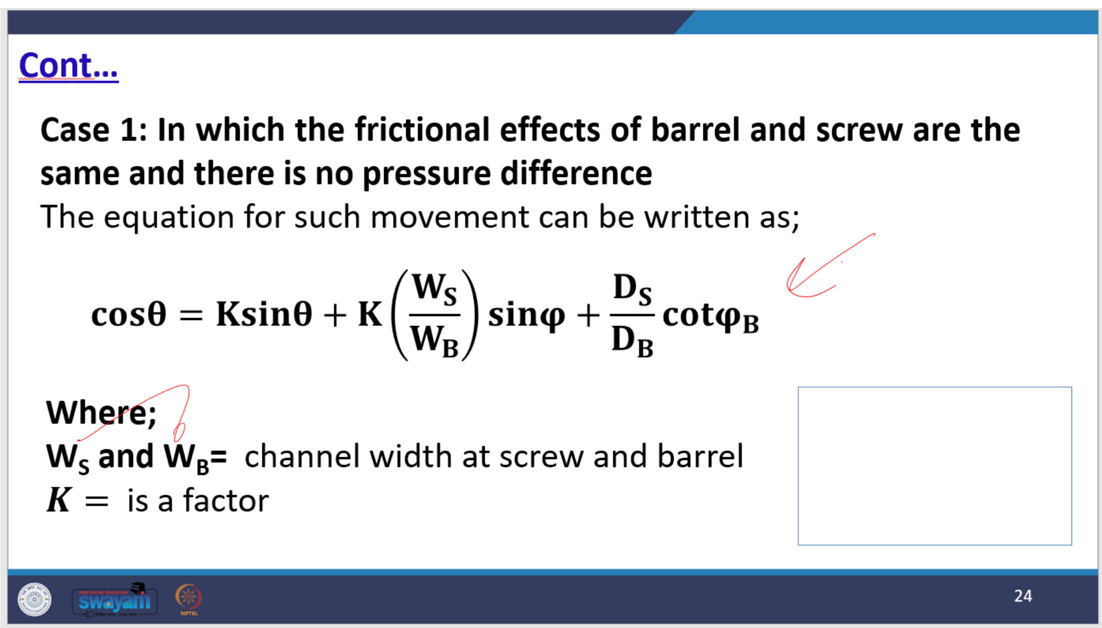
Product	**Pressure (Mpa)**
Cast film	**1.4 – 10.4**
Sheet	**1.5 – 10.4**
Pipe	**2.8 – 10.4**
Blown film	**6.9 – 34.5**
Wire coating	**6.9 – 34.5**
Filament	**6.9 – 20.7**

So, 2.8 to 10.4, then the blown film 6.9 to 34.5, and the wire coating 6.9 to 34. 45 mega Pascal and the filament 6.9 to 20.7. see the variation and this reflects the product and how much they are sensitive towards the pressure. Now another thing is that in the solid conveying section, the best way to describe how the solid particles travel in the feed section is an advance of a solid plug with minimal distortion. So, the basic flow equation of such movement can be represented mathematically like

$$\mathbf{Q_S = \pi^2 N h D_B (D_B - h)\left(\frac{(\tan\theta . \tan\varphi_B)}{\tan\theta + \tan\varphi_B}\right)\left(\frac{W}{W + e}\right)}$$

W is average channel width, psi b is a complicated functional of geometry and this n is the screw speed. Now let us discuss a couple of cases in which in case 1, in which the frictional effect of the barrel and screw are the same and there is no pressure difference. So, the equation for such movement can be mathematically represented as

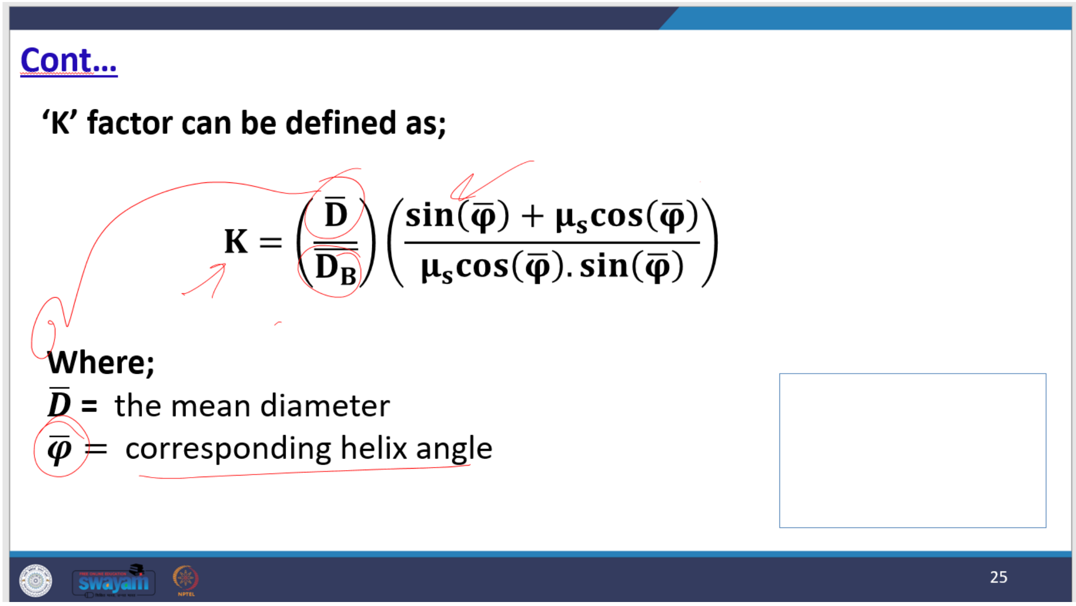
$$\mathbf{\cos\theta = K\sin\theta + K\left(\frac{W_S}{W_B}\right)\sin\varphi + \frac{D_S}{D_B}\cot\varphi_B}$$



where Ws and Wb these are channel width of a screw and barrel and k is a factor. Now this question arises how we can determine the k factor? Now this k factor can be determined as

$$\mathbf{K = \left(\frac{\bar{D}}{\overline{D_B}}\right)\left(\frac{\sin(\bar{\varphi}) + \mu_s\cos(\bar{\varphi})}{\mu_s\cos(\bar{\varphi}).\sin(\bar{\varphi})}\right)}$$

where d is the mean diameter and psi is the corresponding helix angle, we have already discussed the helix angle in the previous slides. Another case in which there is no frictional effect and negligible pressure. So, in that case, all the notations as per the previous discussion, now



$$Q_S = \pi^2 N h D_B (D_B - h)\big((\sin\varphi_B).(\cos\varphi_B)\big)\left(\frac{\bar{W}}{\bar{W} + e}\right)$$

Now for considering the pressure and all possible friction forces given much more complicated expression in theta. Now extruder melting or plasticating, in this particular section the solid is converted into melt. So, again I am emphasizing that the knowledge about the Tm that is the melting temperature and a glass transition temperature is quite essential. Now it is a two-phase section with a proportion for solid and molten material change. Now there are two melting mechanisms, one is that if a screw is above the melting temperature.

Cont…

Case 2: In which there is no frictional effect and negligible pressure

$$Q_S = \pi^2 N h D_B (D_B - h)\left((\sin\varphi_B).(\cos\varphi_B)\right)\left(\frac{\bar{W}}{\bar{W}+e}\right)$$

Note;

For considering of pressure and all possible friction forces gives much more complicated expression in Θ.

So, the solid is surrounded on three sides by a melt film and adjacent to a melt pool. So and second case is that when the screw is below the polymer melting temperature, the film does not exist on two of the solid bed slides. Now in the development of the equation describing the plastication section, this involves the combining of hydrodynamics heat transfer and melting phenomena. Now you see that this particular figure shows the polymer melt mechanism here is the solid bed and this is the melt pool.

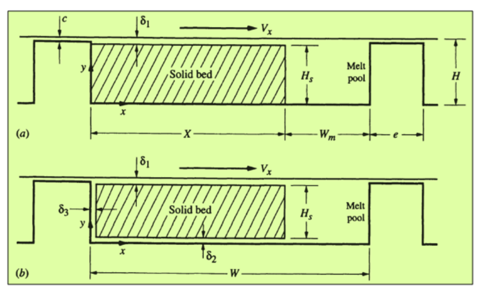
Cont…

If the channel depth is considered to be constant.

The equation for this section can be derived as;

$$\frac{X}{W} = (1 - \left(\frac{C_2 Z}{2\rho_S V_{SZ} h W^{0.5}}\right)^2$$

$$Z_m = \frac{2\rho_S V_{SZ} h W^{0.5}}{C_2} = 2\pi_S V_{SZ} h \left(\frac{2\lambda W}{C_1 \rho m V_x}\right)^{0.5}$$



Fig; Showing polymer melt mechanism

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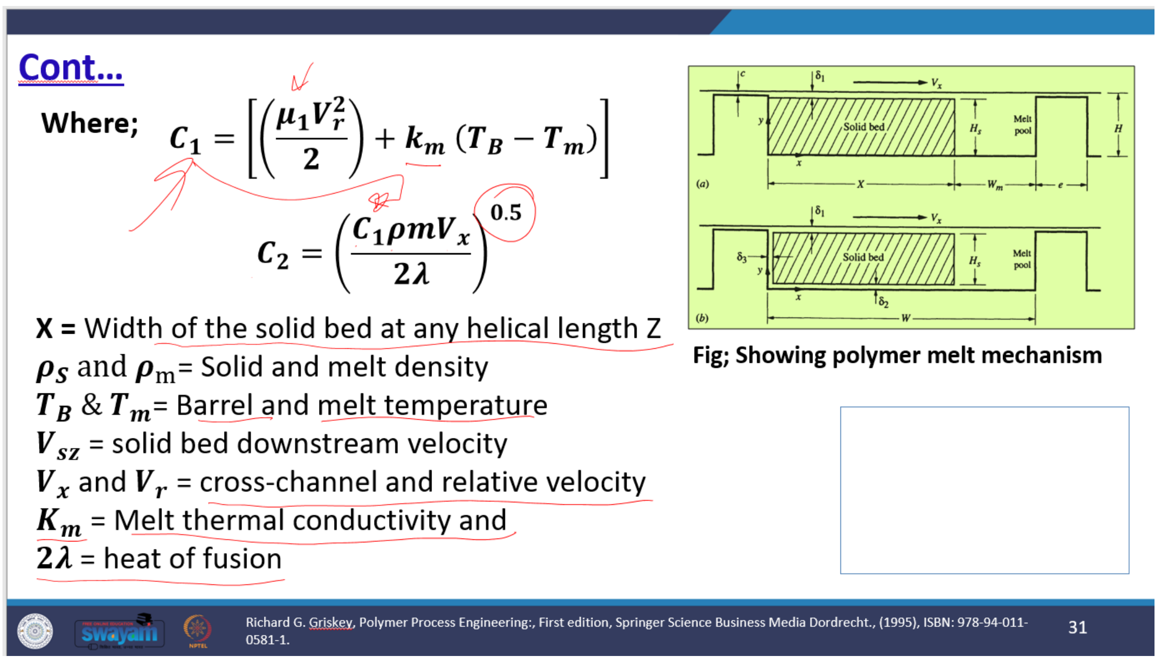
So different segments just need to be addressed. Now if the channel depth is considered to be constant, obviously this is an assumption The equation for this section can be

$$\frac{X}{W} = (1 - \left(\frac{C_2 Z}{2\rho_S V_{SZ} h W^{0.5}}\right)^2$$

$$Z_m = \frac{2\rho_S V_{SZ} h W^{0.5}}{C_2} = 2\pi_S V_{SZ} h \left(\frac{2\lambda W}{C_1 \rho m V_x}\right)^{0.5}$$



Now here we have discussed the two terms C2 and C1.

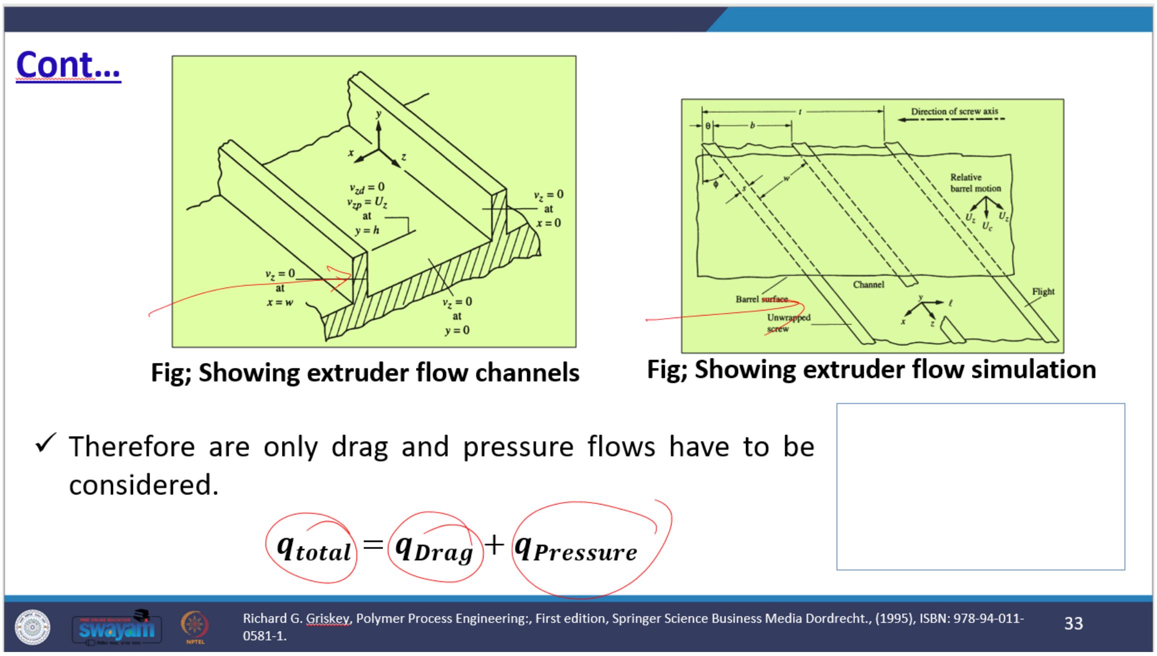
$$C_1 = \left[\left(\frac{\mu_1 V_r^2}{2}\right) + k_m (T_B - T_m)\right]$$

$$C_2 = \left(\frac{C_1 \rho m V_x}{2\lambda}\right)^{0.5}$$

Now here X is the width of the solid bed at any helical length Z. Now ρ_S and ρ_M this is the solid and melt density.

So you must know about this one. Then T_B and T_m this is the barrel and melt temperature. V_{SZ} is the solid bed downstream velocity. V_X and V_r are the cross channel and relative velocity and K_m is the melt thermal conductivity and 2 λ that is the heat of fusion. Now let us talk about the melt or metering zone. In this section the melt polymer flow can be treated by the hydrodynamic analysis and usually, 3 principle flow types that can interact.

One is the drag flow, the melt drags forward in the channel by screw, the pressure flow is backward because backward flow because of the pressure difference in the extruder, and the leakage flow is a backward flow in space between the edge of the flight and the barrel like this. So the leakage flow can happen if the screw flight is corroded or extruded is poorly designed with a significant clearance between the flight edge and barrel. Now this is the barrel and this is this can create the leakage. The drag and pressure flow are typically predominant. Now so therefore only drag and pressure flows have to be considered.



Here you see the extruder flow channels and this is the flow simulation. So when we are considering all these things then

$$q_{total} = q_{Drag} + q_{Pressure}$$

So by semi-empirical approach, if you adopt the semi-empirical approach the ultimate yield is this is Q is a yield.

$$q_{total} = F_D \propto N - F_P \left(\frac{\beta}{\mu}\right)\left(\frac{\partial P}{\partial L}\right)$$

$$\propto \; = \pi^2 D^2 h \left[\frac{1-ne}{2t}\right] sin^2\varphi$$

$$\beta \; = \pi D h^3 \left[\frac{1-ne}{12t}\right] sin^2\varphi$$

Cont...

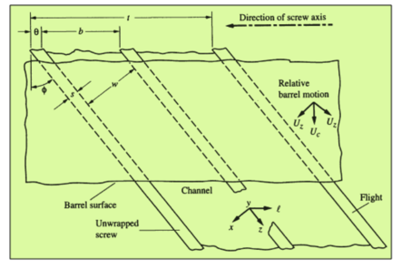
By semiempirical approach, the ultimate yield is;

$$q_{total} = F_D \propto N - F_P \left(\frac{\beta}{\mu}\right)\left(\frac{\partial P}{\partial L}\right)$$

Where;

$$\propto = \pi^2 D^2 h \left[\frac{1 - ne}{2t}\right] sin^2\varphi$$

$$\beta = \pi D h^3 \left[\frac{1 - ne}{12t}\right] sin^2\varphi$$



Fig; Showing extruder flow simulation

- F_P and F_D are the shape factors.
- These above equation are used for isothermal operation and adiabatic cases with energy balance and a Temperature Vs viscosity relations.

This one is alpha. Now alpha is equal to pi square d square H into 1 minus n e upon 2t sine square psi and beta is equal to pi d H cube into 1 minus n e upon 12t sine square sin psi square. Now FP and FD are the shape factors. So here this is the shape factor. Now these above equations are used for isothermal operations and adiabatic cases with energy balance and temperature versus viscosity relations. Now here you see that this is the physical representation of FD and FP on the flow distortion.

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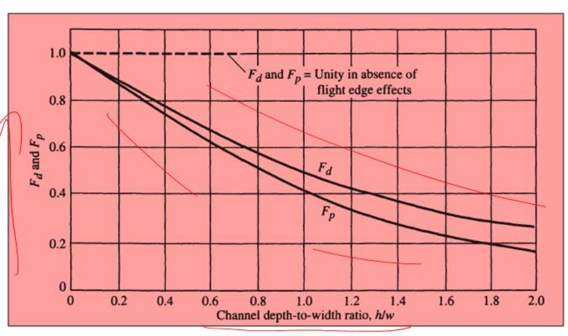
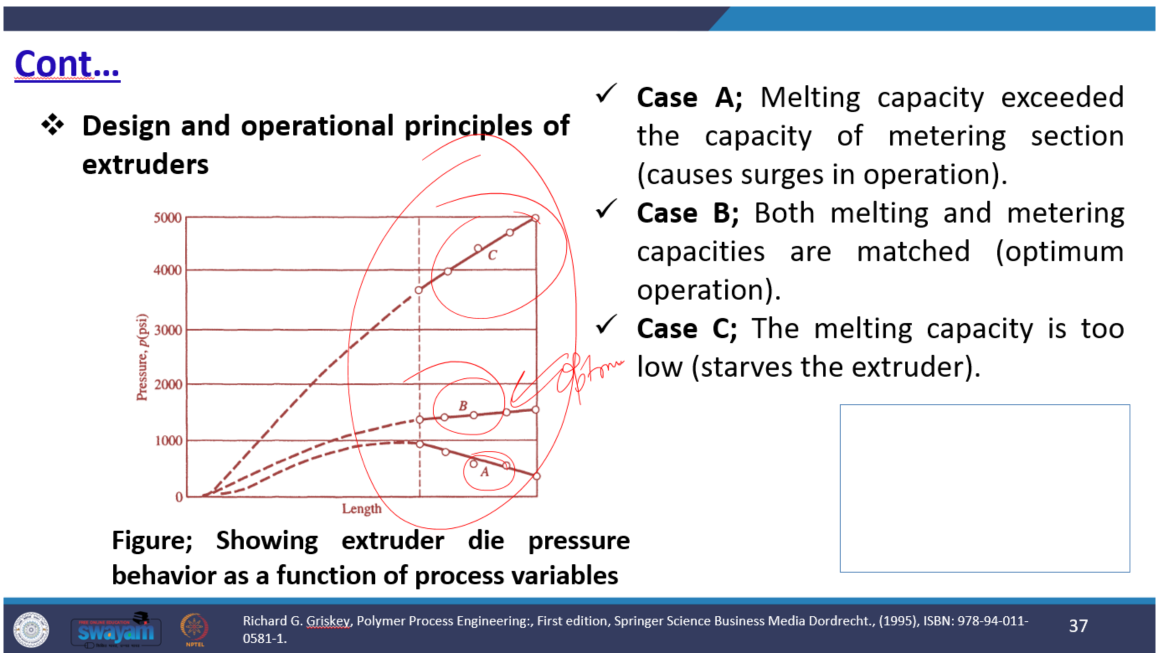
- **Effect of Geometry factors F_D and F_P**



Figure; Physical representation of F_D and F_P on the flow distortion caused by flight edges

This is caused by the flight age. You will see the channel depth and FD and FP and you see the pattern of this one and this reflects the effect of a geometry factor FD and FP. Now there are various principles associated with the design and operational things of extruder. So all these sections like solid conveying, melting, and metering should be properly matched. There must be proper synchronization among all three sections and if they are not then the faulty operation may cause the deformed product. So this figure shows the three cases in such condition length versus pressure and all these things three sections solid conveying, melting and a metering zones they are reflected over here.

This shows the extruder dye pressure behavior as a function of process variables. Now here are different cases in case A the melting capacity exceeded the capacity of the metering section. This causes a surge in operation. Now in this case B, both metering and melting capacities are matched.



This is the optimum operation. Now here in case 3, the melting capacity is too low. This is staff the extruder. So you need to have some optimum values for the smooth operation of your extruder. Now adiabatic operation will give a lower output than the isothermal operation at the given extruder speed and pressure difference. Now for the design or study of extruder operations, there are less elegant design processes available for example

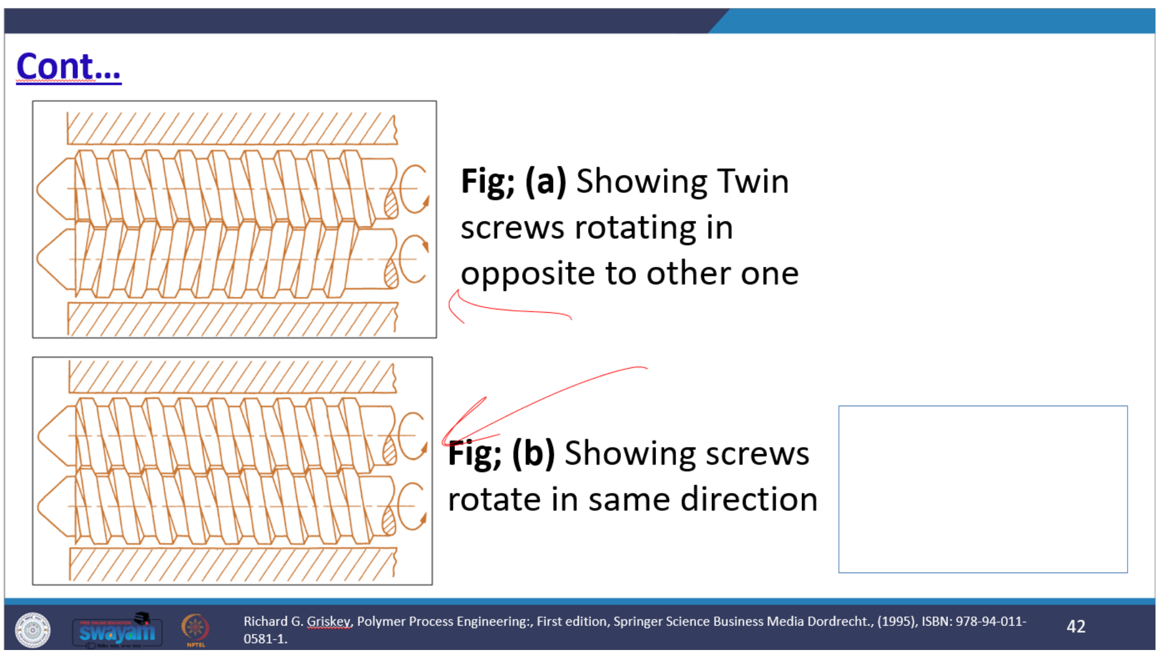
$$\boldsymbol{Power} = \mathbf{0.00053}\boldsymbol{Cq}(\boldsymbol{T_E} - \boldsymbol{T_F})$$

where power is in usually horsepower Q is in pounds per hour C is the average specific heat and usually represented in BTU over pounds for a night and TE and TF are the extruded and the feed temperature. So E represents the extruded and F represents the heat temperature. The minimum screw diameter screw minimum diameter can be determined if surface speed and horsepower power are known.

$$\boldsymbol{D_{min} \cong 4.2\left(\frac{hp}{V_s}\right)}$$

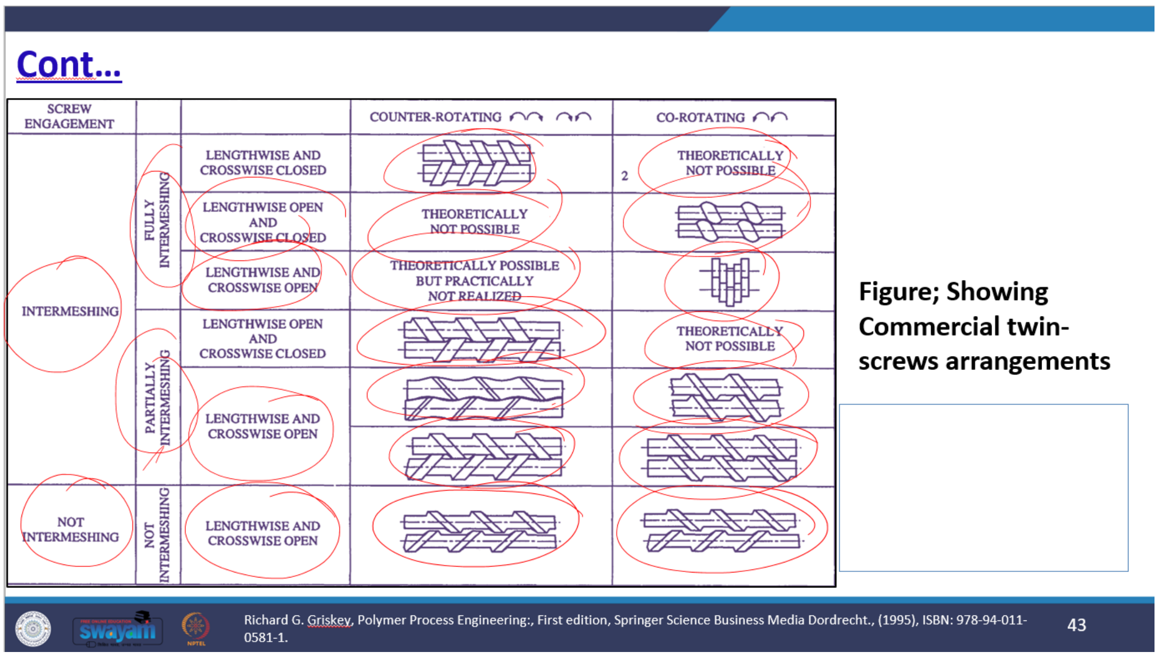
V_S is the surface speed. The length of the extruder again is very important. The length of the extruder is in the ratio L/D ratio of 16 to 24. The longer barrels are favored as they will provide better mixing action. They will have a more uniform at high rates and uniformity of the extruded.

Now let us talk about the twin or multiple screws. The extruder may use twin or multiple screws in their jobs. Now twin extruders can operate with either counter or co-rotating screws. Additionally, the screws can be fully intermeshing partially intermeshing, or non-intermeshing. Now here you see in this first figure this showing the screws the twin screws rotating in opposite to each other.



So it is like this. Here in this particular figure, this reflects the screws rotated in the same direction. Now here you see that there are a couple of things that we would like to have here that are screw engagement intermeshing and non-intermeshing. Now these are the two cases in intermeshing the fully intermeshing and the partially intermeshing. Now the lengthwise the fully intermeshing are subdivided into three aspects.

One is lengthwise and the crosswise is closed like here. This is counter-rotating and theoretically co-rotating is not possible. Then the lengthwise open and the crosswise closed which is not at all possible in the counter-rotating but it is possible in the co-rotating. The lengthwise and the crosswise open are theoretically possible but particularly when you are going for the economic aspect then it is not at all possible like this in the co-rotating. So, when we discuss the partially intermeshing the lengthwise open and the crosswise closed like this you will see that in the counter-rotating and co-rotating is not possible and the lengthwise and the crosswise open you may have like this, and in the co-rotating you may have like this type of the commercial to an arrangement. And when we talk about the non-intermeshing the lengthwise and the crosswise open you may have in the counter-rotating like this and co-rotating like this.



So, this can be categorized related to the size, and shape of the screw channel and a flight such as a non-conjugated and conjugated screw. Non-conjugated screws have flights that fit loosely into the other screw's channel and have ample flow passage so that there will be no locking etc. Now conjugated screws each have flights with a similar size and shape and snugly fit into other screws channel with a negligible clearance. So, they will become more tight.

The flow in the twin screw unit is due to drag and leakage flow. Therefore overall flow is due to the difference between these two flows. The effect of leakage flow is expressed in terms of a percentage of drag flow. The percentage range from the counter-rotating unit is 50 to 65 percent and for the co-rotating unit is 10 to 15 percent. Now the drag flow for counter-rotating units can be represented mathematically like

$$q_d = \pi DhN sin\varphi(\pi D - 2Dh)$$

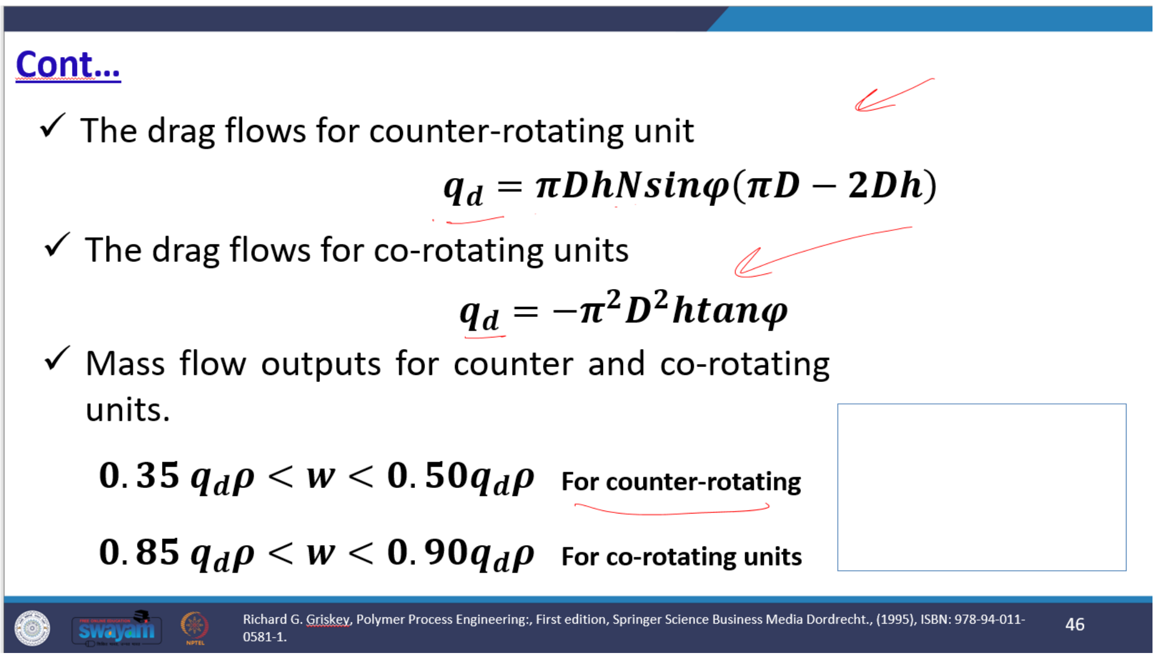
The drag flows for co-rotating units

$$q_d = -\pi^2 D^2 h tan\varphi$$

Mass flow outputs for counter and co-rotating units:

$0.35\ q_d\rho < w < 0.50 q_d\rho$; for counter rotating units

$0.85\ q_d\rho < w < 0.90 q_d\rho$; for co-rotating units



So, dear friends in this particular segment we discussed the basic concepts of extruders, what different kinds of extruders we have what are the basic principles behind them, and what are the integral parts of these extruders so that we can get useful products.

For your convenience, we have enlisted various references which can be utilized for the further study of this particular important segment. Thank you very much.