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Department of Chemical Engineering

Polymers and Plastics Engineering (0905553)

Extruder Characteristics

Metering Zone Analysis

It is convenient to consider the output from the extruder as consisting of three components:

- Drag flow
- Pressure flow
- And leakage

The derivation of the equation for output assumes that in the metering zone the melt has a constant viscosity and its flow is isothermal in a wide shallow channel.

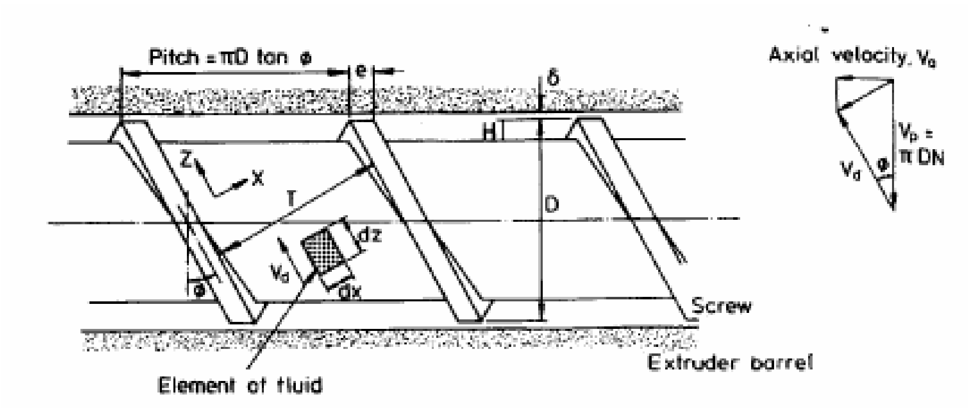

Fig. 1 Details of extruder screw in the metering zone

<u>*Drag flow*</u> can be considered as flow in a slot cross section of depth H, width T, and relative velocity, V_d, between screw and barrel. The volume flow rate along the slot Q_d is given by:

$$Q_d = \frac{1}{2} T H V_d$$

From the geometry of the screw (see Fig. 1) and assuming a rotational speed of N revolutions/second:

$$V_d = \pi D N \cos\phi$$

The pitch of the screw can be calculated using:

$$P = \pi D \tan\phi$$

The width, T, is related to the pitch, P, and flight width, e, as follows:

$$T = (P - e)\cos\phi \approx P\cos\phi \qquad \text{for small } e$$
$$\therefore T \approx \pi D \tan\phi \cos\phi$$
$$T \approx \pi D \sin\phi$$

Therefore:

$$Q_d = \frac{1}{2}\pi^2 D^2 NH \sin\phi\cos\phi \qquad (1)$$

Note that the shear rate in the metering zone will be given by V_d/H.

Pressure flow can be considered as pressure flow between parallel plates. The volume flow rate is as follows:

$$Q_P = -\frac{TH^3}{12\eta_a}\left[\frac{dP}{dz}\right]$$

Where η_a = Newtonian viscosity.

For a linear pressure distribution:

$$\frac{dP}{dz} = \frac{dP}{dl}\frac{dl}{dz} = \frac{dP}{dl}\sin\phi = \frac{P}{l}\sin\phi$$

Where l = length of metering zone.

From the screw geometry (Figure 1):

$$T = \pi D \sin\phi$$

Therefore:

$$Q_P \approx -\frac{\pi D H^3 \sin^2\phi}{12\eta_a}.\frac{P}{l} \qquad (2)$$

Leakage flow takes place between the top of the screw flights and the barrel as a result of the back pressure, and can be analyzed as a pressure flow between parallel plates distance, δ, apart. It is normally small compared with the drag and pressure flow terms and for most practical purposes may be neglected. Its expression is given for completeness.

$$Q_L \approx -\frac{\pi^2 D^2 \delta^3 \tan\phi}{12\eta_a e}.\frac{P}{l} \qquad (3)$$

Total Output

The total output is the combination of drag, back pressure and leakage:

$$Q = \frac{1}{2}\pi^2 D^2 NH \sin\phi\cos\phi - \frac{\pi D H^3 \sin^2\phi}{12\eta_a}.\frac{P}{l} - \frac{\pi^2 D^2 \delta^3 \tan\phi}{12\eta_a e}.\frac{P}{l} \qquad (4)$$

For many practical purposes sufficient accuracy is obtained by neglecting the leakage flow term:

$$Q = \frac{1}{2}\pi^2 D^2 NH \sin\phi \cos\phi - \frac{\pi DH^3 \sin^2\phi}{12\eta_a} \cdot \frac{P}{l} \qquad (5)$$

For a given metering zone screw configuration, i.e. fixed D, H,ϕ, l, this can be written as:

$$Q = C_1 N - C_2 \cdot \frac{P}{\eta_a} \qquad (6)$$

Where l is the extruder length. In practice the length of an extruder screw can vary between 17 and 30 times the diameter of the barrel.

The two extreme operating points are firstly free discharge, i.e. when there is no pressure builds up, thus:

$$Q = C_1 N$$

and secondly when the pressure is large enough to prevent output, in which case:

$$P = \frac{C_1 \eta_a N}{C_2}$$

The characteristic curve is shown in figure 2, which also demonstrates the effects of increasing screw speed, N, and processing a material with higher viscosity, η. Both lead to an increase in the output of the screw for a given operating pressure.

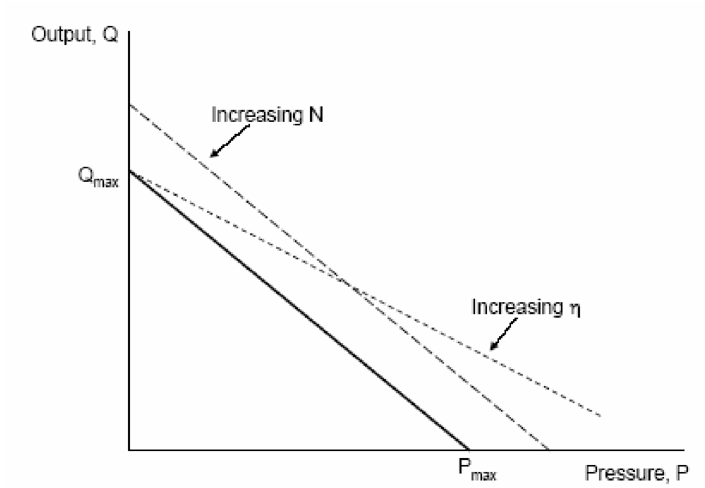

Fig. 2 Characteristic curve for an extruder

As shown in figure 3 the maximum output would be obtained if the screw flight angle was about 35^o. In practice a screw flight angle of 17.7^o is frequently used because:

- This is the angle which occurs if the pitch of the screw is equal to the diameter and so it is convenient to manufacture.

- For a considerable portion of the extruder length, the screw is acting as a solid conveying device and it is known that the optimum angle in such cases is 17^{o} to 20^{o}.

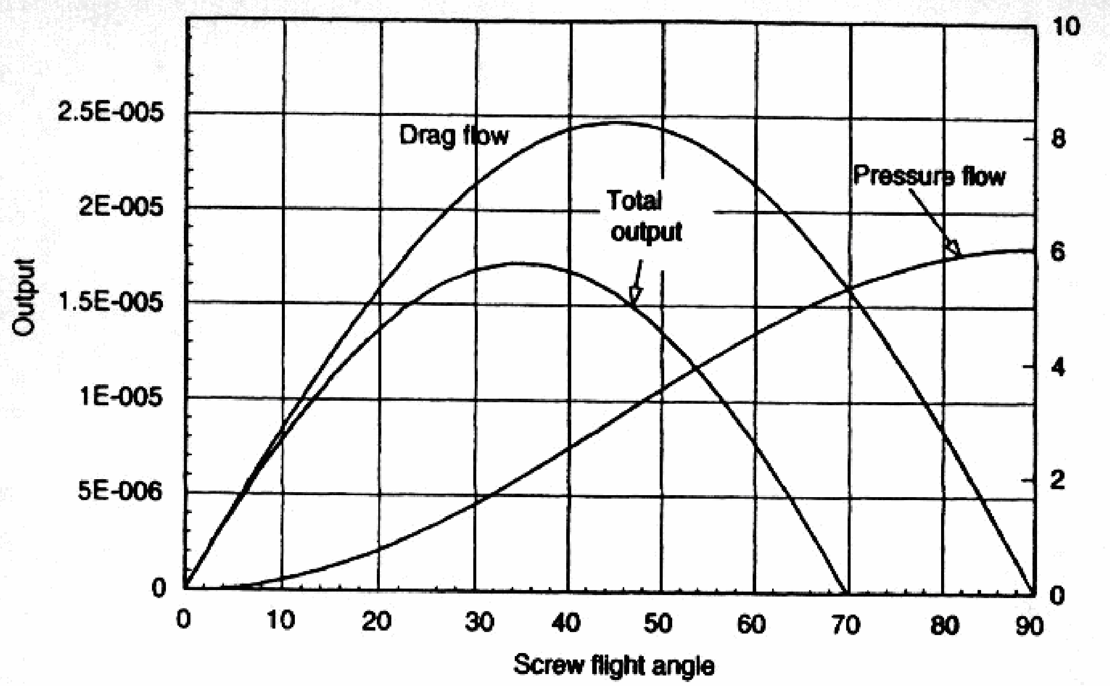

Fig. 3 **Variation of drag flow and pressure flow**

The operating point of a particular extruder is obtained by matching the screw characteristic to the die characteristic.

Die Analysis

The output of a fluid from a die is given by a relation of the form

$$Q = KP$$

For a capillary die of radius R and length L_d the value of $K = \frac{\pi R^4}{8\eta_a L_d}$

$$Q = \frac{\pi R^4 P}{8\eta_a L_d} = -\frac{\pi R^4}{8\eta_a}\frac{dP}{dz} \quad \left(\frac{dP}{dz}\text{ is negative}\right) \qquad (7)$$

This can be written as:

$$Q = C_3 \frac{P}{\eta_a}$$

Operating Point

Equation 7 enables the die characteristics to be plotted with equation 5 on the same graph and the intersection of the two characteristics is the operating point of the extruder. This plot is useful in that it shows the effect which changes in various parameters will have on output.

For example, increasing screw speed, N, will move the extruder characteristic upward. Similarly an increase in the die radius, R, would increase the slope of the die characteristic and in both cases the extruder output would increase.

The operating point for an extruder/die combination may also be determined from:

$$Q = \frac{1}{2}\pi^2 D^2 NH \sin\phi\cos\phi - \frac{\pi DH^3 \sin^2\phi}{12\eta_a}.\frac{P}{l} = \frac{\pi R^4 P}{8\eta_a L_d}$$

So for a capillary die, the pressure at the operating point is given by:

$$P_{OP} = \left\{ \frac{2\pi\eta_a D^2 NH \sin\phi\cos\phi}{\left(\frac{R^4}{2L_d}\right) + \left(\frac{DH^3 \sin^2\phi}{3l}\right)} \right\}$$

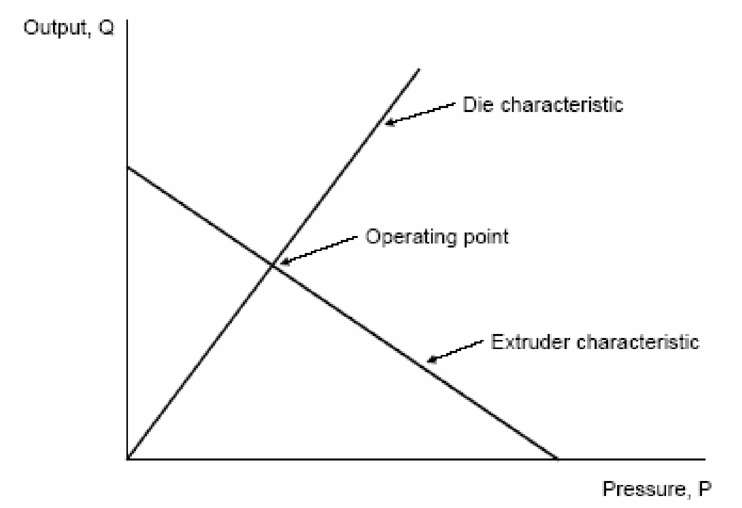

Fig. 4 Extruder and die characteristics

An increase in viscosity has the opposite effect on the die output than on the extruder output, i.e. a reduction. A change in pressure has the opposite effect on the screw and die output resulting in the matched operating point as shown.

Other Die Geometries

For other die geometries it is necessary to use the appropriate form of equation. For other geometries it is possible to use the empirical equation which was developed by Boussinesq. This has the form

$$Q = \frac{Fbd^3}{12\eta_a L_d}.P$$

Where b is the greatest dimension of the cross-section.

d is the least dimension of the cross-section

F is a non-dimensional factor as given in figure 5.

Using the above equation in conjunction with equation 5 it is possible to modify the expression for the operating pressure to the more general from:

$$P_{OP} = \left\{ \frac{2\pi\eta_a D^2 NH \sin\phi \cos\phi}{\left(\left(\frac{Fbd^3}{3\pi L_d}\right) + \left(\frac{DH^3 \sin^2\phi}{3l}\right)\right)} \right\}$$

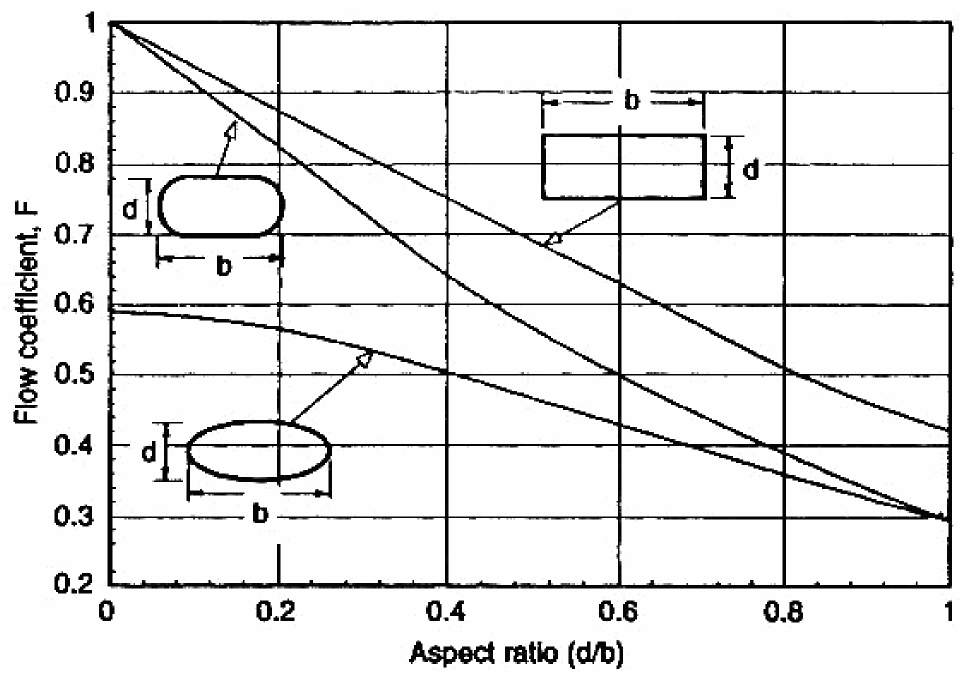

Fig. 5 **Flow coefficient as a function of channel geometry**

Analysis of Film Blowing

It is possible to make a simple estimate of the orientation in blown film by considering only the effects due to the inflation of the bubble. Since the volume flow rate is the same for the plastic in the die and the bubble, then for unit time:

$$\pi D_d h_d L_d = \pi D_b h_b L_b$$

Where *D*, *h* and *L* refer to diameter, thickness and length respectively and the subscript *d* is for the die and *b* is for the bubble.

So the orientation in the machine direction, O_{MD}, is given by

$$O_{MD} = \frac{L_b}{L_d} = \frac{D_d h_d}{h_b D_b}$$

Also the orientation in the traverse direction, O_{TD}, is given by

$$O_{TD} = \frac{D_b}{D_d}$$

Therefore the ration of the orientations may be expresses as:

$$\frac{O_{MD}}{O_{TD}} = \frac{L_b D_d}{L_d D_b} = \frac{D_d^{\ 2} h_d}{h_b D_b^{\ 2}}$$

Analysis of Blow Moulding

When the molten plastic emerges from the die it swells due to the recovery of elastic deformation in the melt.

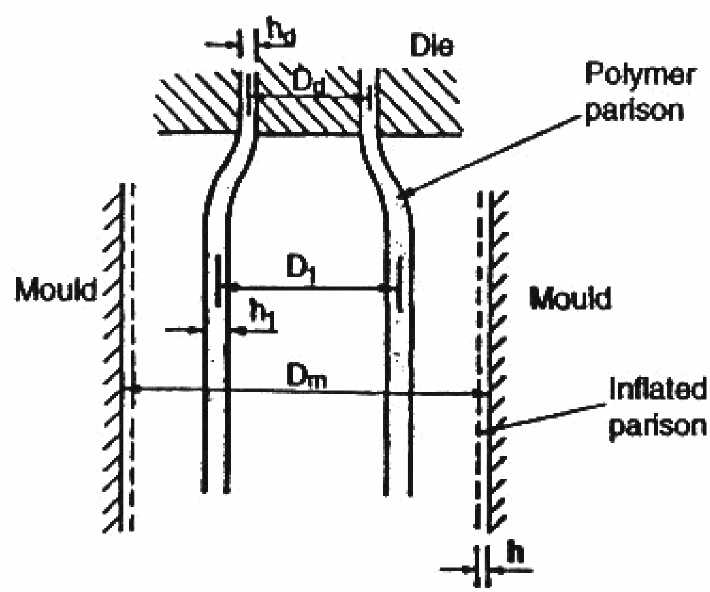

Fig. 6 **Analysis of blow moulding**

$$B_{SH} = B_{ST}^{\ 2}$$

where:

$$B_{SH} = \text{swelling of the thickness} \left(\frac{h_1}{h_d}\right)$$

$$B_{ST} = \text{swelling of the diameter} \left(\frac{D_1}{D_d}\right)$$

Therefore

$$\frac{h_1}{h_d} = \left(\frac{D_1}{D_d}\right)^2$$

$$h_1 = h_d \left(B_{ST}\right)^2$$

Now consider the situation where the parison is inflated to fill a cylindrical die of diameter, D_m. Assuming constancy of volume and neglecting draw-down effects, then:

$$\pi D_1 h_1 = \pi D_m h$$

$$h = \frac{D_1}{D_m} h_1$$

$$h = \frac{D_1}{D_m}\left(h_d B_{ST}{}^2\right)$$

$$h = \frac{B_{ST} D_d}{D_m}\left(h_d B_{ST}{}^2\right)$$

$$h = \frac{D_d}{D_m}\left(h_d B_{ST}{}^3\right)$$

This expression therefore enables the thickness of the moulded article to be calculated from a knowledge of the die dimensions, the swelling ratio and the mould diameter.

Examples:

Q.1) A single screw extruder is to be designed with the following characteristics:

L/D ratio = ***24***

Screw flight angle = ***17.7^o***

Max. screw speed = ***100 rev/min***

Screw diameter = ***40 mm***

Flight depth (metering zone) = ***3 mm***

If the extruder is to be used to process polymer melts with a maximum melt viscosity of ***500 Ns/m^2***, *calculate a suitable wall thickness for the extruder barrel* based on the Mises yield criterion. The tensile stress for the barrel metal is ***925 MN/m^2*** and a factor of safety of ***2.5*** should be used.

Q.2) A single screw extruder is to be used to manufacture a nylon rod ***5 mm*** in diameter at a production rate of ***1.5 m/min***. Using the following information, *calculate the required screw speed*.

Nylon	***Extruder***	***Die***
Viscosity = ***420 Ns/m^2***	Diameter = ***30 mm***	Length = ***4 mm***
Density (solid) = ***1140 kg/m^3***	Length = *750 mm*	Diameter = ***5 mm***
Density (melt) = ***790 kg/m^3***	Screw flight angle = ***17.7^o***	
	Metering channel depth = ***2.5 mm***	

Die swelling effects may be ignored and the melt viscosity can be assumed to be constant.

Q.3) A plastic shrink wrapping with a thickness of ***0.05 mm*** is to be produced using an annular die with a die gap of ***0.8 mm***. Assuming that the inflation of the bubble dominates the orientation in the film, *determine the blow-up ration* required to give uniform biaxial orientation.

Q.4) A blow moulding die has an outside diameter of ***30 mm*** and an inside diameter of ***27 mm***. The parison is inflated with a pressure of ***0.4*** $\boldsymbol{MN/m^2}$ to produce a plastic bottle of diameter ***50 mm***. If the extrusion rate used causes a thickness swelling ratio of ***2***, *estimate the wall thickness of the bottle*. Comment on the suitability of the production conditions if melt fracture occurs at a stress of ***6*** $\boldsymbol{MN/m^2}$.