HANSER

Sample Pages

Natti S. Rao, Nick R. Schott

Understanding Plastics Engineering Calculations

Hands-on Examples and Case Studies

ISBN: 978-3-446-42278-0

For further information and order see

http://www.hanser.de/978-3-446-42278-0

or contact your bookseller.

4 Analytical Procedures for Troubleshooting Extrusion Screws

Extrusion is one of the most widely used polymer converting operations for manufacturing blown film, pipes, sheets, and laminations, to list the most significant industrial applications. Fig. 4.1 shows a modern large scale machine for making blown film. The extruder, which constitutes the central unit of these machines, is shown in Fig. 4.2. The polymer is fed into the hopper in the form of granulate or powder. It is kept at the desired temperature and humidity by controlled air circulation. The solids are conveyed by the rotating screw and slowly melted, in part, by barrel heating but mainly by the frictional heat generated by the shear between the polymer and the barrel (Fig. 4.3). The melt at the desired temperature and pressure flows through the die, in which the shaping of the melt into the desired shape takes place.

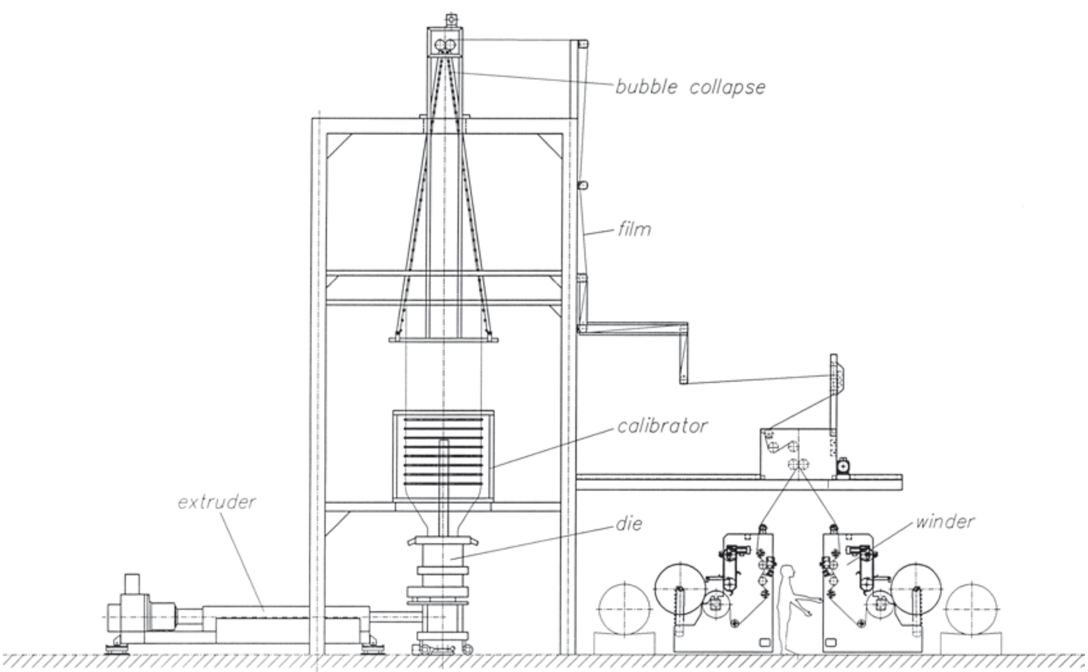

FIGURE 4.1 Large scale blown film line [2]

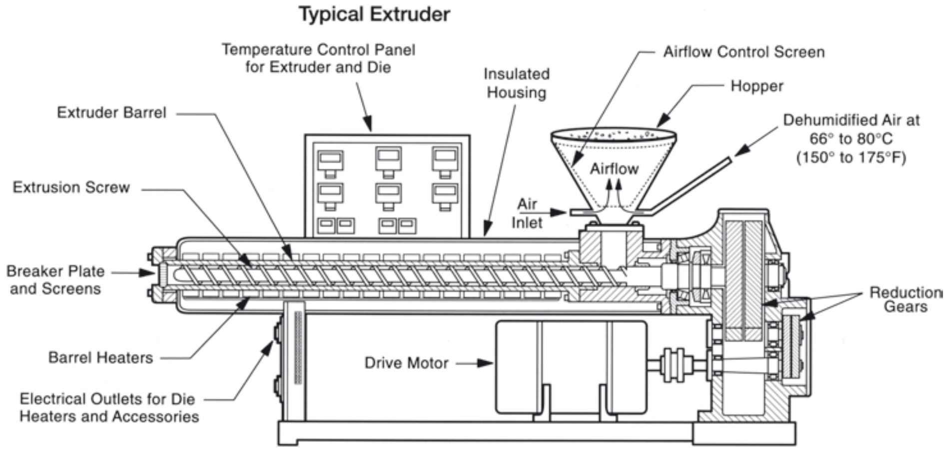

FIGURE 4.2 Extruder with auxialiary equipment [3]

4.1 Three-Zone Screw

Basically extrusion consists of transporting the solid polymer in an extruder by means of a rotating screw, melting the solid, homogenizing the melt, and forcing the melt through a die (Fig. 4.3).

The extruder screw of a conventional plasticating extruder has three geometrically different zones (Fig. 4.4), whose functions can be described as follows:

Feed zone:	Transport and preheating of the solid material
Transition zone:	Compression and plastication of the polymer
Metering zone:	Melt conveying, melt mixing and pumping of the melt to the die

However, the functions of a zone are not limited to that particular zone alone. The processes mentioned can continue to occur in the adjoining zone as well.

Although the following equations apply to the 3-zone screws, they can be used segmentwise for designing screws of other geometries as well.

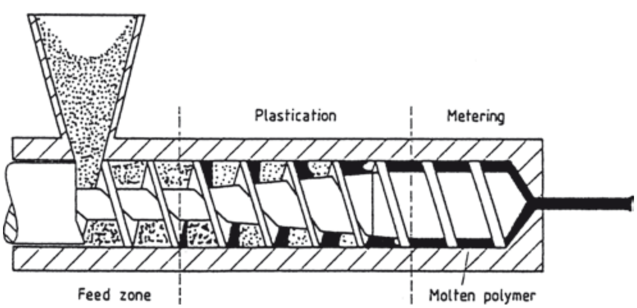

FIGURE 4.3 Plasticating extrusion [4]

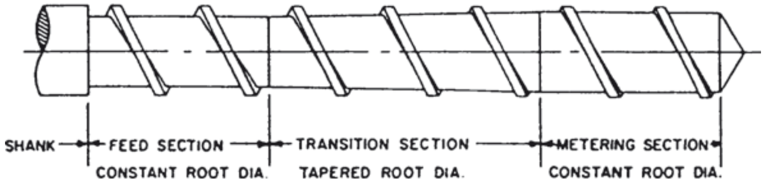

FIGURE 4.4 Three-zone screw [10]

4.1.1 Extruder Output

Depending on the type of extruder, the output is determined either by the geometry of the solids feeding zone alone, as in the case of a grooved extruder [7], or by the solids and melt zones to be found in a smooth barrel extruder. A too high or too low output results when the dimensions of the screw and die are not matched with each other.

4.1.2 Feed Zone

A good estimate of the solids flow rate can be obtained from Eq. (4.1) as a function of the conveying efficiency and the feed depth. The desired output can be found by simulating the effect of these factors on the flow rate by means of Eq. (4.1).

Calculated Example

The solids transport is largely influenced by the frictional forces between the solid polymer and barrel and screw surfaces. A detailed analysis of the solids conveying mechanism was performed by Darnell and Mol [8]. The following example presents an empirical equation that provides good results in practice [1].

The geometry of the feed zone of a screw (Fig. 4.5) is given by the following data:

Barrel diameter	D_b	= 30 mm
Screw lead	s	= 30 mm
Number of flights	ν	= 1
Flight width	w_{FLT}	= 3 mm
Channel width	W	= 28.6 mm
Depth of the feed zone	H	= 5 mm
Conveying efficiency	η_F	= 0.436
Screw speed	N	= 250 rpm
Bulk density of the polymer	ρ_o	= 800 kg/m^3

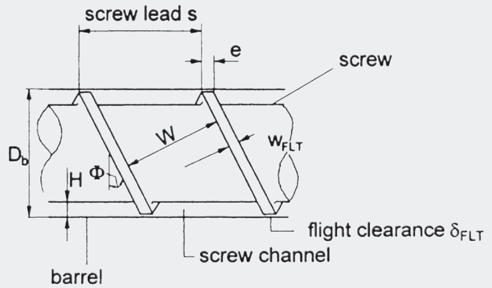

FIGURE 4.5 Screw zone of a single screw extruder [5]

The solids conveying rate in the feed zone of the extruder can be calculated according to [4]

$$G = 60 \cdot \rho_o \cdot N \cdot \eta_F \cdot \pi^2 \cdot H \cdot D_b \left(D_b - H\right) \frac{W}{W + w_{FLT}} \cdot \sin\phi \cdot \cos\phi \tag{4.1}$$

with the helix angle ϕ

$$\phi = \tan^{-1}\left[s / \left(\pi \cdot D_b\right)\right] \tag{4.2}$$

The conveying efficiency η_F in Eq. (4.1) as defined here is the ratio between the actual extrusion rate and the theoretical maximum extrusion rate attainable under the assumption of no friction between the solid polymer and the screw. It depends on the type of polymer, bulk density, barrel temperature, and the friction between the polymer, barrel and the screw. Experimental values of η_F for some polymers are given in Table 4.1.

TABLE 4.1 Conveying efficiency η_F for some polymers

Polymer	Smooth barrel	Grooved barrel
LDPE	0.44	0.8
HDPE	0.35	0.75
PP	0.25	0.6
PVC-P	0.45	0.8
PA	0.2	0.5
PET	0.17	0.52
PC	0.18	0.51
PS	0.22	0.65

Using the values above with the dimensions in meters in Eq. (4.1) and Eq. (4.2) we get

$$G = 60 \cdot 800 \cdot 250 \cdot 0.44 \cdot \pi^2 \cdot 0.005 \cdot 0.03 \cdot 0.025 \cdot \frac{0.0256}{0.0286} \cdot 0.3034 \cdot 0.953$$

Hence $G \approx 50$ kg/h

■

6.2.3 Screw Dimensions

Essential dimensions of injection molding screws for processing thermoplastics are given in Table 6.6 for several screw diameters [1].

TABLE 6.6 Significant Screw Dimensions for Processing Thermoplastics

Diameter (mm)	Flight depth (feed) h_F (mm)	Flight depth (metering) h_M (mm)	Flight depth ratio	Radial flight clearance (mm)
30	4.3	2.1	2 : 1	0.15
40	5.4	2.6	2.1 : 1	0.15
60	7.5	3.4	2.2 : 1	0.15
80	9.1	3.8	2.4 : 1	0.20
100	10.7	4.3	2.5 : 1	0.20
120	12	4.8	2.5 : 1	0.25
> 120	max 14	max 5.6	max 3 : 1	0.25

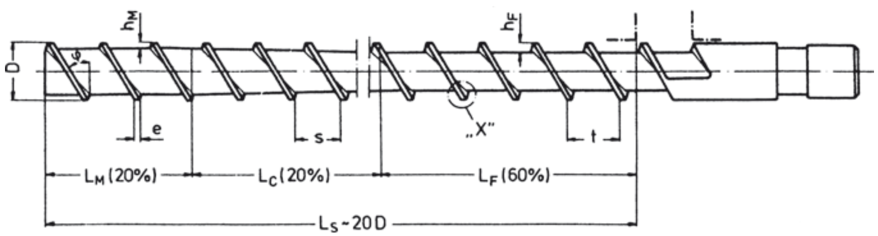

FIGURE 6.8 Dimensions of an injection molding screw [1]

6.3 Injection Mold

The problems encountered in injection molding are often related to mold design whereas in extrusion, the screw design determines the quality of the melt as discussed in Chapter 5.

The quantitative description of the important mold filling stage has been made possible by the well-known software MOLDFLOW [10]. The purpose of this section is to present practical calculation procedures that can be handled even by handheld calculators.

6.3.1 Runner Systems

The pressure drop along the gate or runner of an injection mold [15] can be calculated from the same relationships used for dimensioning extrusion dies (Chapter 5).

Calculated Example

For the following conditions, the isothermal pressure drop Δp_0 and the adiabatic pressure drop Δp are to be determined:

For polystyrene with the following viscosity constants according to [29]

A_0 = 4.4475

A_1 = –0.4983

A_2 = –0.1743

A_3 = 0.03594

A_4 = –0.002196

c_1 = 4.285

c_2 = 133.2

T_0 = 190 °C

flow rate	$\dot{m}$	= 330.4 kg/h
melt density	ρ_m	= 1.12 g/cm³
specific heat	c_{pm}	= 1.6 kJ/(kg · K)
melt temperature	T	= 230 °C
length of the runner	L	= 101.6 mm
radius of the runner	R	= 5.08 mm

Solution:

a) Isothermal flow

$\dot{\gamma}_a$ from

$$\dot{\gamma}_a = \frac{4\,\dot{Q}}{\pi\,R^3} = \frac{4 \cdot 330.0}{3.6 \cdot \pi \cdot 1.12 \cdot 0.508^3} = 795.8\ \text{s}^{-1}$$

($\dot{Q}$ = volume flow rate cm³/s)

a_T from

$$a_T = 10^{\frac{-c_1 (T - T_0)}{c_2 + (T - T_0)}} = 10^{\frac{-4.285 (230-190)}{133.2 + (230-190)}} = 10^{-0.9896} = 0.102$$

Power law exponent [29]

$$n = 5.956$$

$\eta_{a,}$ viscosity [29]

$$\eta_a = 132\ \text{Pa} \cdot \text{s}$$

τ shear stress

$$\tau = 105013.6 \text{ Pa}$$

K:

$$K = 9.911 \cdot 10^{-28}$$

Die constant G_{circle} from Table 1.4

$$G_{\text{circle}} = \left(\frac{\pi}{4}\right)^{\frac{1}{5.956}} \cdot \frac{\left(5.08 \cdot 10^{-3}\right)^{\frac{1}{5956}+1}}{2 \cdot 0.1016} = 1.678 \cdot 10^{-3}$$

Δp_0 with $\dot{Q} = 8.194 \cdot 10^{-5}\ \text{m}^3/\text{s}$ from Equation 5.1:

$$\Delta p_0 = \frac{10^{-5} \cdot \left(8.194 \cdot 10^{-5}\right)^{\frac{1}{5.956}}}{\left(9.911 \cdot 10^{-28}\right)^{\frac{1}{5.956}} \cdot 1.678 \cdot 10^{-3}} = 42 \text{ bar}$$

b) Adiabatic flow

The relationship for the ratio $\frac{\Delta p}{\Delta p_0}$ is [17]

$$\frac{\Delta p}{\Delta p_0} = \frac{\ln \chi_L}{\chi_L - 1}$$

where

$$\chi_L = 1 + \frac{\beta \cdot \Delta p_0}{\rho_m \cdot c_{pm}}$$

Temperature rise from Equation (5.20):

$$\Delta T = \frac{\Delta p}{10 \cdot \rho_m \cdot c_{pm}} = \frac{42}{10 \cdot 1.12 \cdot 1.6} = 2.34 \text{ K}$$

For polystyrene

$$\beta = 0.026 \text{ K}^{-1}$$

$$\chi_L = 2.34 \cdot 0.026 = 1.061$$

Finally, Δp

$$\Delta p = \Delta p_0 \frac{\ln \chi_L}{\chi_L - 1} = \frac{42 \cdot \ln 1.061}{0.061} = 40.77 \text{ bar}$$

■

In the adiabatic case, the pressure drop is smaller because the dissipated heat is retained in the melt.

6.3.2 Mold Filling

As already mentioned, the mold filling process is treated extensively in commercial simulation programs and by Bangert [13]. In the following sections the more transparent method of Stevenson is given with an example.

To determine the size of an injection molding machine in order to produce a given part, knowledge of the clamping force exerted by the mold is important, as this force should not exceed the clamping force of the machine.

Injection Pressure

The isothermal pressure drop for a disc-shaped cavity is given as [14]

$$\Delta p_1 = \frac{K_r}{10^5\left(1-n_R\right)}\left[\frac{360\cdot\dot{Q}\cdot\left(1+2\cdot n_R\right)}{N\cdot\Theta\cdot 4\,\pi\cdot n_R\cdot r_2\cdot b^2}\right]^{n_R}\cdot\left(\frac{r_2}{b}\right) \tag{6.10}$$

The fill time τ is defined as [14]

$$\tau = \frac{V\cdot a}{\dot{Q}\cdot b^2} \tag{6.11}$$

The Brinkman number is given by [14]

$$Br = \frac{b^2\cdot K_r}{10^4\cdot\lambda\cdot\left(T_M-T_W\right)}\cdot\left(\frac{\dot{Q}\cdot 360}{N\cdot\Theta\cdot 2\,\pi\cdot b^2\cdot r_2}\right)^{1+n_R} \tag{6.12}$$

Calculated Example with Symbols and Units

Given data:

The part has the shape of a round disc.

The material is ABS with n_R = 0.2565, which is the reciprocal of the power law exponent n. The constant K_r, which corresponds to the viscosity η_p, is $K_r = 3.05 \cdot 10^4$.

Constant injection rate	$\dot{Q}$	= 160 cm³/s
Part volume	V	= 160 cm³
Half thickness of the disc	b	= 2.1 mm
Radius of the disc	r_2	= 120 mm
Number of gates	N	= 1

Inlet melt temperature	T_M	= 518 K
Mold temperature	T_W	= 323 K
Thermal conductivity of the melt	λ	= 0.174 W/(m·K)
Thermal diffusivity of the polymer	a	= $7.72 \cdot 10^{-4}$ cm²/s
Melt flow angle [14]	Θ	= 360°

The isothermal pressure drop in the mold Δp_1 is to be determined.

Solution:

Applying Eq. (6.10) for Δp_1

$$\Delta p_1 = \frac{3.05 \cdot 10^4}{10^5 \left(1 - 0.2655\right)} \left[\frac{360 \cdot 160 \cdot \left(1 + 2 \cdot 0.2655\right)}{1 \cdot 360 \cdot 4\,\pi \cdot 12 \cdot 0.105^2}\right]^{0.2655} \cdot \left(\frac{12}{0.105}\right) = 254 \text{ bar}$$

Dimensionless fill time τ from Eq. (6.11):

$$\tau = \frac{160 \cdot 7.72 \cdot 10^{-4}}{160 \cdot 0.105^2} = 0.07$$

Brinkman number from Eq. (6.12):

$$Br = \frac{0.105^2 \cdot 3.05 \cdot 10^4}{10^4 \cdot 0.174 \cdot 195} \cdot \left(\frac{160 \cdot 360}{1 \cdot 360 \cdot 2\,\pi \cdot 0.105^2 \cdot 12}\right)^{1.2655} = 0.771$$

From the experimental results of Stevenson [14] the following empirical relation was developed to calculate the actual pressure drop in the mold

$$\ln\left(\frac{\Delta p}{\Delta p_1}\right) = 0.337 + 4.7\,\tau - 0.093\,Br - 2.6\,\tau \cdot Br \tag{6.13}$$

The actual pressure drop Δp is therefore from Eq. (6.13)

$$\Delta p = 1.574 \cdot \Delta p_1 = 1.574 \cdot 254 = 400 \text{ bar}$$

Clamping Force

The calculation of clamping force is similar to that of the injection pressure. First, the isothermal clamping force is determined from [14]

$$F_1\left(r_2\right) = 10 \cdot \pi \cdot r_2^2 \left(\frac{1 - n_R}{3 - n_R}\right) \cdot \Delta p_1 \tag{6.14}$$

where $F_1(r_2)$ = isothermal clamping force (N).

$F_1(r_2)$ for the example above is with Eq. (6.14)

$$F_1(r_2) = 10 \cdot \pi \cdot 12^2 \left(\frac{1 - 0.2655}{3 - 0.2655} \right) \cdot 254 = 308.64 \text{ kN}$$

The actual clamping force can be obtained from the following empirical relationship, which was developed from the results published in [14].

$$\ln\left(\frac{F}{F_1}\right) = 0.372 + 7.6\,\tau - 0.084\,Br - 3.538\,\tau\,Br \qquad (6.15)$$

Hence the actual clamping force F from Eq. (6.15)

$$F = 1.91 \cdot 308.64 = 589.5 \text{ kN}$$

The above relationships are valid for a disc-shaped cavity. Other geometries of the mold cavity can be taken into account on this basis in the manner described by Stevenson [14].

6.4 Flow Characteristics of Injection Molding Resins

One of the criteria for resin selection to make a given part is whether the melt is an easy flowing type or whether it exhibits significantly viscous behavior. To determine the flowability of the polymer melt, the spiral test, which consists of injecting the melt into a spiral shaped mold shown in Fig. 6.9, is used. The length of the spiral serves as a measure of the ease of flow of the melt in the mold, and enables mold and part design suited to material flow.

The parameters involved in the flow process are resin viscosity, melt temperature, mold wall temperature, axial screw speed, injection pressure, and geometry of the mold. To minimize the number of experiments required to determine the flow length, a semi-empirical model based on dimensional analysis is given in this section. The modified dimensionless numbers used in this model taking non-Newtonian melt flow into account are the Graetz number, Reynolds number, Prandtl number, Brinkman number, and Euler number. Comparison between experimental data obtained with different thermoplastic resins and the model predictions showed good agreement, confirming the applicability of the approach to any injection molding resin [28].

The experimental flow curves obtained at constant injection pressure under given melt temperature, mold temperature, and axial screw speed are given schematically in Fig. 6.10 for a resin type at various spiral depths with melt flow rate of the polymer brand as a parameter. By comparing the flow lengths with one another at any spiral depth also called wall thickness, the flowability of the resin brand in question with reference to another brand can be inferred [8, 18].