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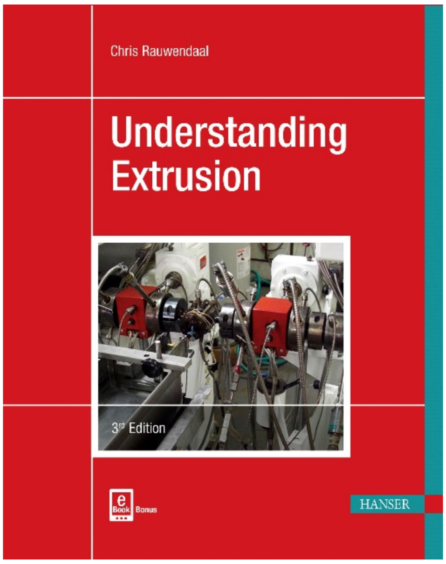

Sample Pages

Understanding Extrusion

Chris Rauwendaal

ISBN (Book): 978-1-56990-698-9
ISBN (E-Book): 978-1-56990-699-6

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Preface to the Third Edition

The first edition of Understanding Extrusion was published in 2000 and the second edition in 2010. Since the second edition was issued several important developments have taken place. As a result, it makes sense to have a third edition of Understanding Extrusion.

Most of the new material is incorporated in Chapter 2. Topics included in this chapter are interpretation of extrusion process data, dimensional variation by melt temperature fluctuations, efficient extrusion, and more. Chapters 7 and 8 have also been extended and now cover topics such as analysis of shrink void formation and grooved barrel extruder technology.

I would like to thank Dr. Mark Smith for his encouragement to work on this third edition. I also want to thank my wife Sietske for her continued support and for putting up with me despite these time-consuming projects.

Chris Rauwendaal

September 2018

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1.3 Components of an Extruder

In this section we will discuss:

- the extruder screw
- the extruder barrel
- the feed throat
- the feed hopper
- barrel heating and cooling
- the breaker plate
- the screen pack
- the extrusion die
- the extruder drive
- the reducer
- gear pumps
- instrumentation and control

1.3.1 The Extruder Screw

The heart of the extruder is the extruder screw. This is a long cylinder with a helical flight wrapped around it, see Figure 1.6. The screw is very important because conveying, heating, melting, and mixing of the plastic are mostly determined by the screw. The stability of the process and the quality of the extruded product are very much dependent on the design of the screw. The screw rotates in a cylinder that fits closely around it.

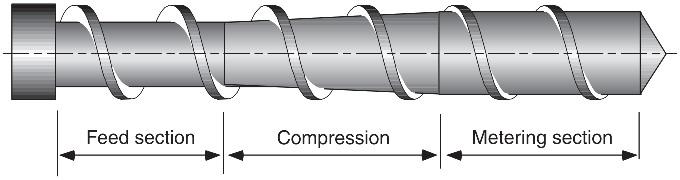

Figure 1.6 A single flighted extruder screw

1.3.2 The Extruder Barrel

The cylinder is called the extruder barrel. The barrel is a straight cylinder usually equipped with a bimetallic liner; this liner is a hard, integral layer with high wear resistance. In most cases, the wear resistance of the barrel should be better than that of the screw. The reason is that the screw is much easier to rebuild and replace than the barrel. Bimetallic barrels usually cannot be rebuilt.

Functions

The barrel may have a vent opening through which volatiles can be removed from the plastic, see Figure 1.7, a process called devolatilization. An example is the removal of moisture from a hygroscopic plastic. An extruder with a vent port should use a special screw geometry to keep the plastic melt from coming out of the vent port; such a screw is called a “two-stage screw,” see Figure 1.7.

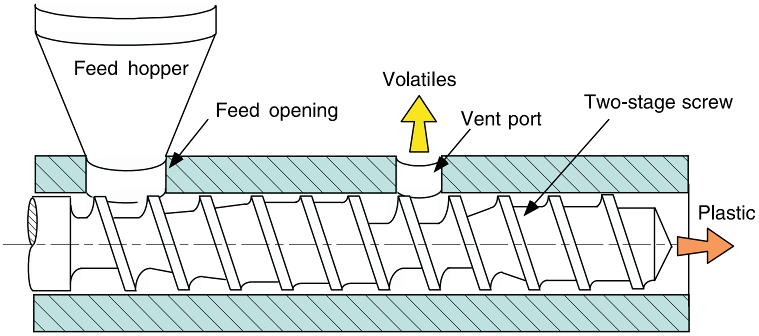

Figure 1.7 A vented extruder barrel with a two-stage screw

1.3.3 The Feed Throat

Material intake

The feed throat is connected to the barrel; it contains the feed opening through which the plastic material is introduced to the extruder. The feed throat usually has water-cooling capability because we have to be able to keep the feed throat temperature low enough to keep the plastic particles from sticking to the wall. To improve the intake capability of the feed throat, the feed opening can be offset as shown in Figure 1.8 and have an elongated shape. The length of the feed opening should be about 1.5 times the diameter of the barrel and the width about 0.7 times the diameter.

Some extruders do not have a separate feed throat, but the feed opening is machined right into the extruder barrel. There are both advantages and disadvantages to such a setup. The advantages are lower cost, fewer parts, and no problems with alignment of the barrel to the feed throat. Disadvantages are that it is more difficult to create a thermal barrier between the hot barrel and the cold feed throat region and good cooling of the feed throat region is more difficult.

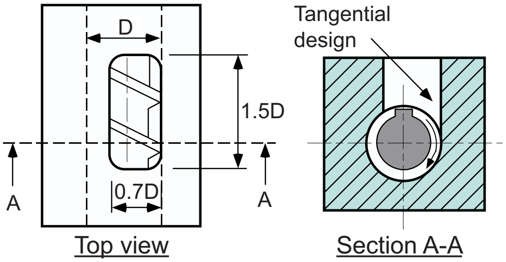

Figure 1.8 Preferred geometry for feed opening in the feed throat

1.3.4 The Feed Hopper

Conveying material

The feed throat is connected to the feed hopper and the extruder barrel. The feed hopper holds the plastic pellets or powder and discharges the material into the feed throat. The hopper should be designed to allow a steady flow of material. Steady flow is best achieved with a circular hopper with a gradual transition in the conical section of the hopper, see Figure 1.9.

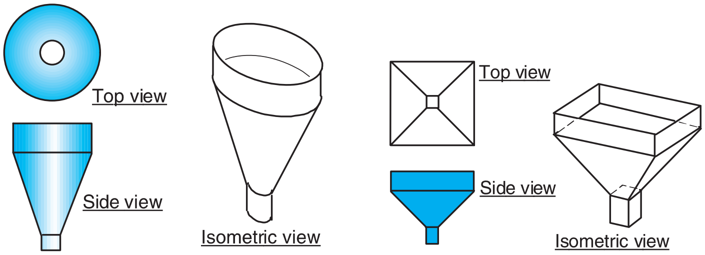

Figure 1.9 Good hopper design (left) and bad hopper design (right)

For difficult bulk materials, special devices can be used to promote steady flow through the hopper; such as vibrating pads, stirrers, wipers, and even crammer screws to force the material to the discharge, see Figure 1.10.

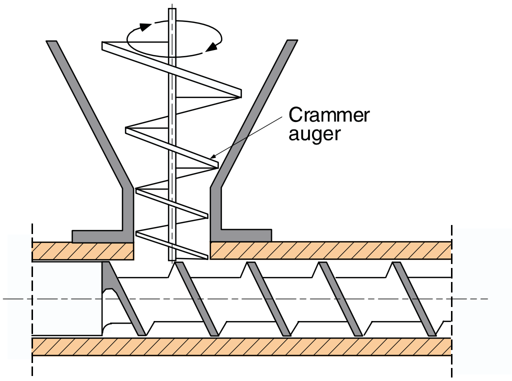

Figure 1.10
Example of crammer feeder

1.3.5 Barrel Heating and Cooling

Various heating methods

The extruder barrel has both heating and cooling capability. Heating is usually done with electrical band heaters located along the length of the extruder. The heaters can be mica insulated heaters, ceramic heaters, or cast-in heaters. In cast-in heaters, the heating elements are cast in a semi-circular block of aluminum or bronze; these heaters provide good heat transfer. Aluminum cast heaters can heat up to 400 °C, while bronze cast heaters have a maximum operating temperature of about 550 °C. Other types of heating can be used, such as induction heating, The threaded probe with the sapphire window can be used in combination with a simple IR thermometer. This allows IR melt temperature measurement in the extruder barrel or in the die.

IR temperature measurement provides two important benefits: 1) fast response, 2) no disturbance of flow

IR temperature measurement provides two important benefits. One, the response time is fast, about 10 milliseconds. Two, the measurement does not disturb the flow as is the case with an immersion probe. Because of the fast response, the IR measurement can detect rapid changes in melt temperature that cannot be detected by an immersion melt temperature probe. Melt temperature variation will be discussed next.

Melt Temperature Variation in Extrusion

The melt temperatures in extrusion result from viscous dissipation and heat transfer. In drag flow, the shear rates and viscous dissipation are relatively uniform. However, the heat transfer to the screw and barrel results in large temperature differences within the polymer melt. The largest temperature gradients tend to occur at the barrel surface.

Melt temperature distribution can be determined by performing a non-isothermal analysis of the flow in the screw channel

The melt temperature distribution can be determined by performing a non-isothermal analysis of the flow in the screw channel. In the case of a non-Newtonian polymer melt this is typically done using finite element analysis (FEA). Figure 2.24 shows a color contour plot of melt temperatures in the screw channel of a 63 mm single screw extruder running a 0.2 melt index high density polyethylene (HDPE) at 100 rpm. The vertical axis has been stretched about eight times to make it easier to examine the temperature distribution.

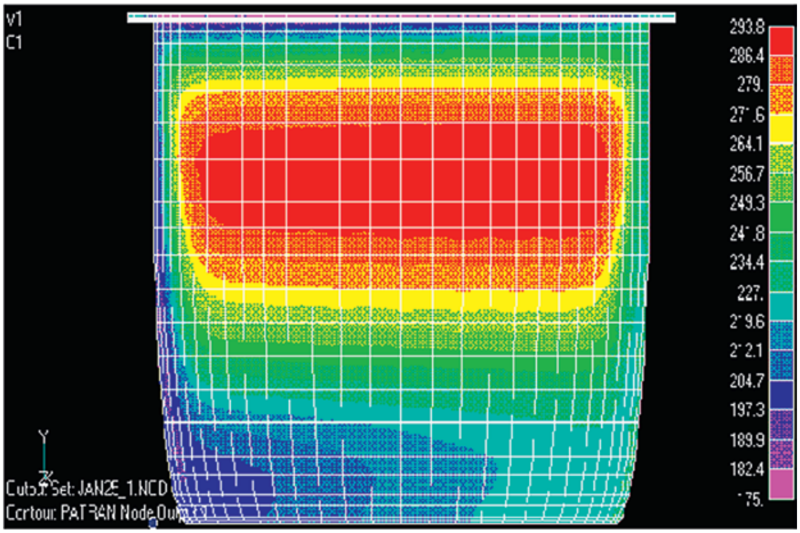

Figure 2.24 Melt temperature distribution in 63 mm extruder running at 100 rpm

Melt temperatures in the screw channel are highly non-uniform

The top surface is the barrel, the bottom surface is the root of the screw, the left vertical boundary is the pushing flank of the flight, and the right vertical boundary is the trailing flank of the flight. It is clear that the melt temperatures are highly non-uniform. The temperatures close to the barrel are relatively low because of the heat transfer to the barrel – the barrel cools down the melt that is in close proximity to the barrel. The temperatures at the pushing flight flank are low because the cool melt close to the barrel moves down along the flight when it reaches the pushing flight flank.

At the root of the screw, the cool melt from the pushing flight flank moves toward the trailing side of the flight. If there is no heat transfer with the screw, the melt temperatures will gradually increase as the melt moves from the pushing flank to the trailing flank. The melt reaching the trailing flight flank moves up along the flight until it gets close to the barrel. At that point the cycle starts again. The outer region of the screw channel stays relatively cool because of the heat transfer from the melt to the barrel. The situation is quite different for the inner region of the screw channel.

The melt in the inner region remains in this region as it travels down the length of the screw channel – it will not come into close proximity of the barrel. The inner region is thermally insulated from the barrel by a relatively thick layer of polymer melt. As a result, the temperatures in this region increase higher than in any other part of the channel – it is a natural hot spot. In Figure 2.24 the temperatures in the hot spot are more than 100 °C above the barrel temperature.

Hot spots tend to form in the center region of the screw channel

When the screw discharges the melt, this melt will be non-uniform in temperature. A number of studies have analyzed the variation of melt temperatures in extruders. One such study was made by E. Brown and A. Kelly at Bradford University in England. In this work, a fast response thermocouple (TC) mesh was used to measure melt temperature variation using three different extruder screws. The TC mesh was located in the breaker plate recess of the extruder barrel, see Figure 2.25.

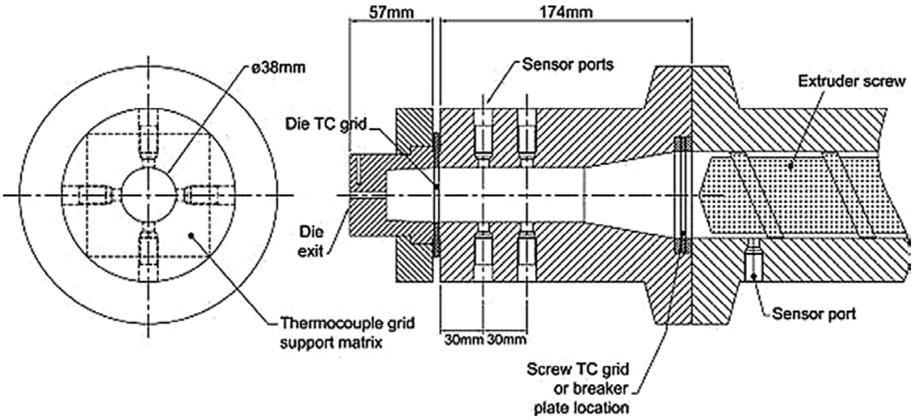

Figure 2.25 Experimental setup for melt temperature study

Melt temperature was measured at multiple locations, see Figure 2.26. It is clear from this figure that the melt temperatures across the channel are quite non-uniform with a low temperature of 190 °C and a high temperature over 215 °C.

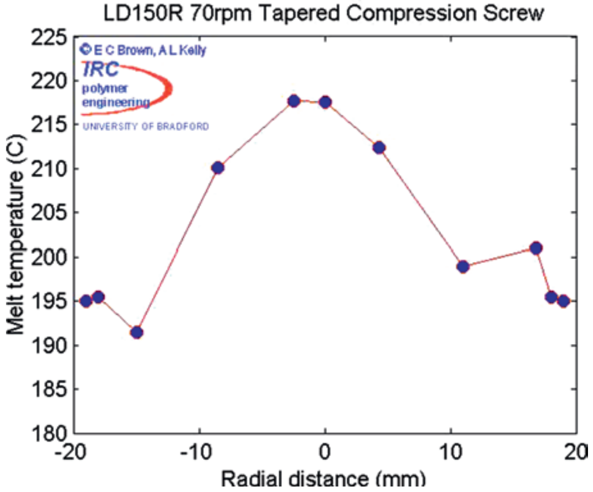

Figure 2.26 Melt temperatures versus radial distance from the center

The melt temperatures vary not only across the melt stream but also over time – this is shown in Figure 2.27.

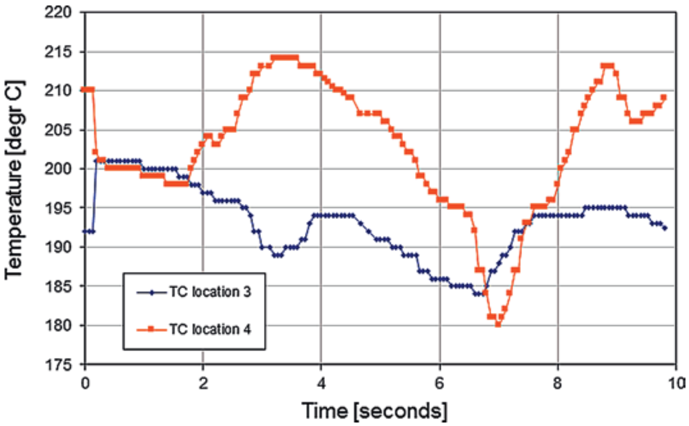

Figure 2.27 Melt temperature versus time

The melt at TC4 (radial location –10 mm in Figure 2.26) drops from 215 °C to 180 °C within four seconds and then increases again to almost 215 °C within two seconds. This is rapid and substantial melt temperature variation! Interestingly, this melt temperature variation cannot be detected with an immersion melt temperature probe because of the slow response time.

In this study, the melt temperatures were also measured with an infrared thermometer. The results are shown in Figure 2.28.

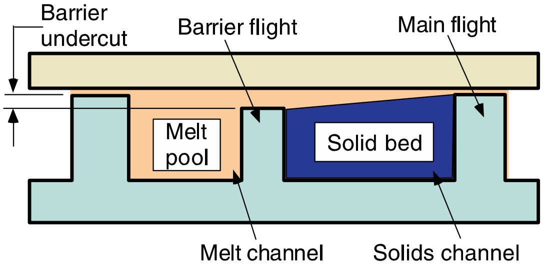

Figure 5.14 Cross section of a barrier screw

Pre-heating material

One variable that affects the melting in an extruder is the temperature at which the plastic is introduced to the extruder. By preheating the plastic in the feed hopper or before, the amount of heat that has to be added to melt the plastic in the extruder is reduced and, as a result, melting occurs earlier in the extruder. When it is suspected that an extrusion problem is related to melting, preheating is a method of diagnosing the problem.

Barrier screw advantages

The barrier screw has the following advantages:

- The barrier screw achieves more stable extrusion than a simple conveying screw.
- With a barrier screw, there is virtually no chance of unmelted material beyond the barrier section.
- There is a certain amount of dispersive mixing that occurs as the plastic melt flows over the barrier flight into the melt channel.

Disadvantages

Next to these advantages, there are the following disadvantages:

- Barrier screws are no better in performance than non-barrier screws designed with effective mixing sections.
- Barrier screws tend to be more expensive than non-barrier screws, particularly when purchased from an original equipment manufacturer (OEM).
- Because the solid material is restricted to the solids channel, the barrier screw is inherently more susceptible to plugging. This occurs when melting cannot keep up with the reduction in the size of the channel in the compression section of the screw, resulting in the solid material getting stuck in the screw channel. This creates a momentary obstruction to flow and leads to surging. Surging is a variation in extruder output.

5.3 Melt Conveying

Mechanisms of conveying

Melt conveying starts when the melting is completed in the extruder. Strictly speaking, melt conveying starts when melting starts, because the melting zone is where we have both solids conveying and melt conveying with the amount of solid material gradually decreasing and, at the same time, the amount of melted material gradually increasing. However, we define the melt-conveying zone as the region where all the plastic is completely melted.

The mechanism of melt conveying is viscous drag. In other words, the viscous forces acting on the plastic melt are responsible for the forward conveying of the melt. As we saw in the solids conveying zone, the viscous force at the barrel is responsible for forward conveying, while the viscous force at the screw is a retarding force. As a result, melt conveying is improved by reducing the barrel temperature and increasing the screw temperature. Interestingly, screw heating in the melt conveying zone makes more sense than barrel heating.

Optimum screw geometry

The optimum screw geometry for melt conveying can be determined from extrusion theory. The optimum helix angle is dependent only on the degree of non-Newtonian behavior of the plastic melt; it can be determined from the following expression:

$$\text{optimum helix angle}\left[\text{degrees}\right]=13.5+16.5\ (\text{power law index}) \tag{5.1}$$

Optimum helix angle

The optimum helix angle for melt conveying decreases as the power law index decreases or the plastic is more shear thinning. A similar expression can be derived for the optimum depth of the channel in the melt-conveying zone. The optimum depth depends on the viscosity, the pressure gradient, and the power law index. When the plastic becomes more shear thinning, the channel depth should be reduced to maintain good melt conveying.

5.3.1 Melt Temperatures

Predicting melt temperature by FEA

Because of the low thermal conductivity of the plastic melts, the temperatures in the melt-conveying zone can vary substantially. Local temperatures are difficult to measure because it is hard to put a probe in the screw channel while the screw is rotating. Melt temperatures can be predicted from extrusion theory using numerical techniques. A popular technique for this purpose is finite element analysis (FEA). With this technique the flow patterns and temperature distribution can be predicted.

Distribution of melt temperature

Figure 5.15 depicts the temperature distribution in the screw channel by looking at a cross section of the screw channel. The temperatures are shown in colors; different colors represent different temperatures, just like the weather map on the back page of USA Today. The lower surface of the picture is the root of the screw; the upper surface is the extruder barrel. The barrel is maintained at 175 °C and the screw surface is considered insulated (adiabatic). It can be seen in the figure that the highest melt temperatures occur in the mid-region of the channel, while the outside region of the channel remains at a lower temperature.

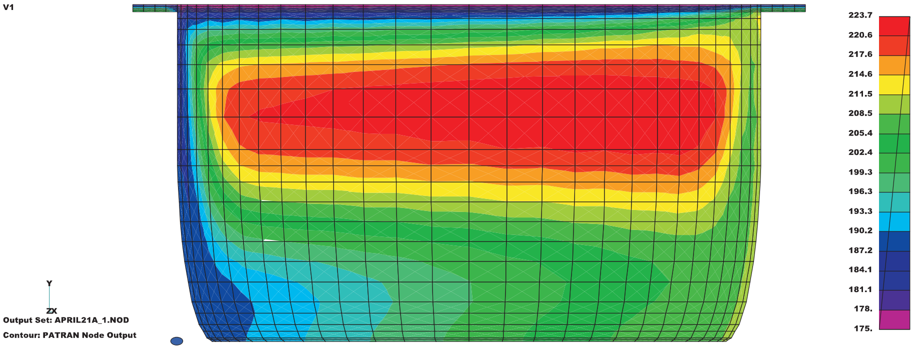

Figure 5.15 Predicted melt temperatures in the screw channel

The reason for this temperature distribution is the way the plastic melt flows along the screw channel. We can illustrate this flow by unrolling the screw channel and by looking at it as a straight trough (see Figure 5.16) and the barrel as a flat plate.

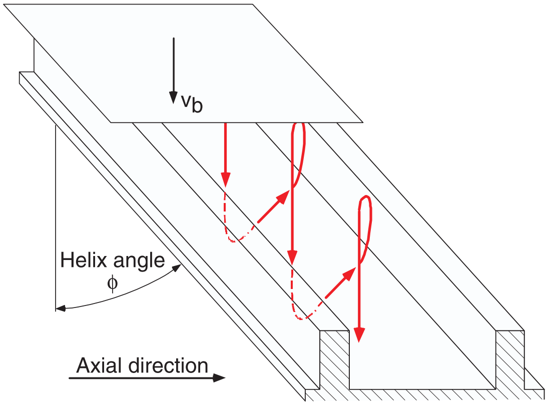

Figure 5.16 Flow along the unrolled screw channel

Movement of fluid element through the barrel

If we look at the flow relative to the screw, then the barrel moves in tangential direction, v_b, making an angle ϕ with the channel. Angle ϕ is the helix angle of the screw flight. A fluid element close to the barrel surface flows in the direction of the barrel until it gets to the pushing side of the flight. At this point, the element moves downward and then crosses the screw channel. When the element gets to the trailing side of the flight, the element moves up again close to the barrel surface and the element starts moving in the direction of the barrel again. This pattern repeats itself numerous times as long as the regular flight geometry is maintained.

Different types of flow through channel

If we look at the flow in the cross section of the screw channel (see Figure 5.17), we see the material moves to the pushing side of the flight at the top of the channel. This flow results from drag flow. At the bottom of the channel, the material moves toward the trailing side of the flight. This is a pressure flow resulting from the fact that the pressure at the pushing side of the flight is higher than at the trailing side of the flight. If the leakage flow through the flight clearance is negligible, the amount of material flowing to the pushing flight flank is the same as the amount of material flowing to the trailing flight flank. Thus, we get a recirculating flow[1] as shown in Figure 5.17.

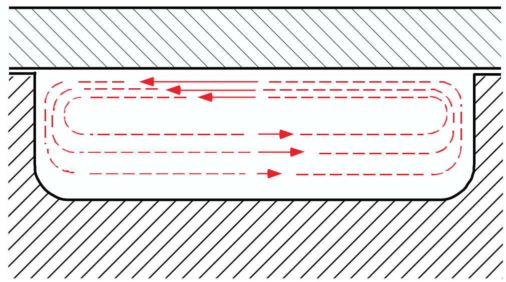

Figure 5.17 Recirculating flow in the cross section of the screw channel

Melt temperature close to surface

The fluid is sheared as it flows along the screw channel and, as a result, there is viscous heat generation in the plastic melt. The actual temperatures that occur at different points in the screw channel are determined not only by viscous heating, but also by how efficiently this heat can be removed. If the barrel is cooled, the melt flowing close to the barrel surface can exchange heat and cool down efficiently. When this outer layer moves along the screw surface, it remains relatively cool even if the screw is insulated.

Melt temperature of inner layer

However, the situation is quite different for the inner layer. Because this layer is trapped in the inner recirculating region, it never gets close to the barrel. As a result, this layer has very limited opportunity for removal of its heat; the outer layer of plastic melt essentially insulates the inner layer. This explains why the temperature in the inner region of the screw channel tends to be higher than in the outer region. In Figure 5.15, the temperature in the center region is about 60 °C higher than the barrel temperature. Thus, it is clear that considerable melt temperature differences can occur in the screw channel.

If these temperature differences are carried to the end of the screw, the melt discharged into the die is not thermally homogeneous. This leads to flow problems in the die and distortion of the extruded product. It is important, therefore, to try to keep these non-uniform melt temperatures from reaching the end of the screw.

Importance of homogeneous melt temperature

The most efficient method to do this is by incorporating mixing elements into the design of the screw. Mixing sections are not only important when we mix different plastics, but also when we extrude a single plastic in order to achieve a thermally homogeneous melt at the end of the screw.

---

[1] There are also small velocity components in the normal direction close to the flight flanks. At the pushing flight flank, the normal flow is downward toward the root of the screw; at the trailing flight flank, the normal flow is upward, toward the barrel. The normal flow also results from pressure differences. For instance, the pressure at the top of the pushing flight flank is higher than at the bottom of the flight flank, which is why the flow is downward in this region.

5.4 Mixing

Mixing in the melt stage

Mixing takes place both in the melting zone as well as in the melt-conveying zone of the extruder. The solid plastic typically moves in plug flow, which means that there is no relative motion between the solid plastic particles. As a result, there is little or no mixing in solids conveying. This means that complete mixing does not start until all the plastic has melted. For this reason, we will look at mixing only in the melt conveying zone of the extruder.

5.4.1 Distributive Mixing

Definition

The extent of distributive mixing can be determined from the total shear deformation of the plastic melt in the melt conveying zone. The total shear deformation is also called the total shear strain; it is determined by the product of the shear rate and the length of time that the fluid is exposed to the shear rate. For instance, if the plastic melt is exposed to a shear rate of 100 s^{-1} for 15 seconds, the resulting shear strain is 100 × 15 = 1500. The shear strain is dimensionless. The shear rate is determined by the velocity profiles in the extruder.

Mixing in single screw extruders is determined mostly by the two main velocity components in the screw channel. These are the velocity in the direction of the channel (z-direction) and the velocity in the cross-channel direction (x-direction), see Figure 5.18.

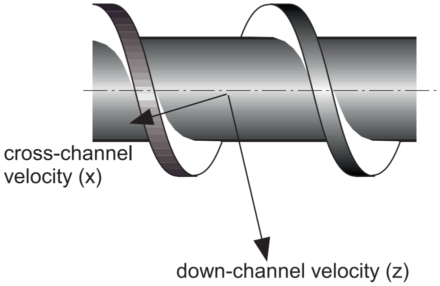

Figure 5.18
The two main flow components in a single screw extruder

Pressure gradient

There is also a velocity component in the third direction (y-direction) parallel to the flight flank. This velocity component is usually very small and therefore can usually be neglected. The velocities in the down-channel direction depend on the pressure gradient; this can be positive, zero, or negative. When the pressure gradient is positive, pressure is increasing along the melt conveying zone; when the pressure gradient is negative, pressure is decreasing along the melt conveying zone. Down-channel velocity profiles for different values of the pressure gradient are shown in Figure 5.19.

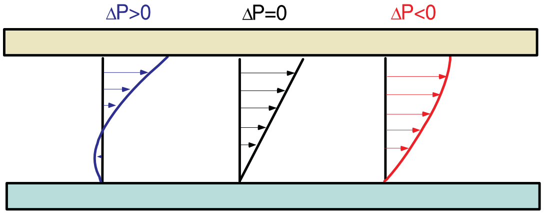

Figure 5.19 Down-channel velocity profiles for three pressure conditions

Types of flow

The cross-channel flow is shown in Figure 5.17. At the top of the channel, the material flows to the left by drag flow and at the bottom of the channel, the material flows to the right by pressure flow. Figure 5.20 shows the cross-channel velocities.

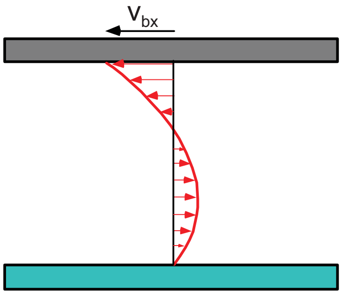

Figure 5.20
Cross-channel velocity profile

Shear rate

The shear rate can be determined from the velocity profile; the shear rate is equal to the slope of the velocity profile. This slope of the velocity profile is also called the velocity gradient. From the down-channel velocities, we can determine the down-channel shear rates; these are shown in Figure 5.21.

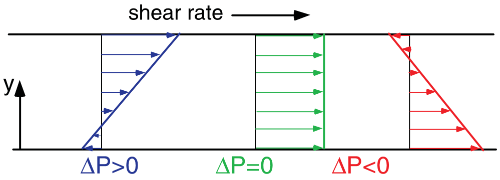

Figure 5.21 Down-channel shear rates for three pressure conditions

When the pressure gradient is positive, the shear rates increase toward the barrel surface; when the pressure gradient is zero, the shear rate is constant, and when the pressure gradient is negative, the shear rates decrease toward the barrel surface. The same approach can be used to determine the cross-channel shear rate from the cross-channel velocities. The cross-channel shear rate profile is shown in Figure 5.22.

6.8 Inspection and Training

Proper training

It is the responsibility of the employer to establish and follow a program of periodic inspections of the extruder to ensure that all safeguards are in proper operating condition. The employer must also train operators in safe extruder operation before actually working on one. An effective training program should include the following four steps:

- Tell workers how to do it safely
- Show them the safe way to do it
- Encourage them to ask questions
- Have them show you that they know how to do it safely

Three important rules regarding safety training:

- Never assume that employees know how to carry out a new task
- Frequent reminders should be given concerning safety procedures
- Never assume that safety rules are remembered

Checklists

It is good practice to have regular safety inspections, at least once a quarter. The objective is to identify as many safety and health hazards as possible before they can cause an accident. The following checklist can be used for a successful safety inspection.

Housekeeping

Housekeeping

☐ Is the work place clean and orderly?
☐ Are floors free from protruding nails, holes, and loose boards?
☐ Are the aisles and passageways kept clear of obstructions?
☐ Are permanent aisles and passageways clearly marked?
☐ Are covers or guardrails in place around open pits, tanks, and ditches?

Floor and wall openings

Floor and wall openings

☐ Are ladder ways and door openings guarded by a railing?
☐ Do skylights have screens or fixed railings?
☐ Do temporary floor openings have standard railings or guards?
☐ Are wall openings with a drop of more than 1.2 meter (4 feet) guarded by a railing?
☐ Do all stairways with four or more risers have a handrail?
☐ Are stairways strong enough, adequately illuminated, and slip resistant?

Escape routes

Escape routes

☐ Are there enough exits to allow prompt escape?
☐ Do employees have easy access to exits?
☐ Are exits unlocked to allow people to leave?
☐ Are exits and exit routes equipped with emergency lighting?

Personal protective equipment

Personal protective equipment

☐ Is the required equipment provided, maintained, and used?

☐ Does the equipment meet requirements and is it reliable?

Employee facilities

Employee facilities

☐ Are facilities kept clean and sanitary?

☐ Are toilets kept clean and in good repair?

☐ Are cafeteria facilities a sufficient distance from toxic materials?

Medical and first aid

Medical and first aid

☐ Is there a hospital, clinic, or infirmary nearby?

☐ Are employees trained in first aid on each shift?

☐ Are physician-approved first aid supplies available?

☐ Are first aid supplies replenished as they are used?

Fire protection

Fire protection

☐ Are fire extinguishers available for the types of fire most likely to occur?

☐ Are there enough fire extinguishers available to do the job?

☐ Are fire extinguisher locations clearly marked?

☐ Are fire extinguishers properly mounted and easily accessible?

☐ Are all fire extinguishers fully charged and operable?

☐ Are special purpose extinguishers clearly marked?

Material handling and storage

Material handling and storage

☐ Is adequate clearance allowed in aisles?

☐ Are stacked materials interlocked, locked, and limited in height to maintain stability?

☐ Are storage areas kept free of tripping, fire, explosion, and pest hazards?

☐ Is proper drainage provided?

☐ Are signs warning of clearance limits posted?

☐ Are powered industrial truck operators adequately trained?

Machine guarding and signs

Machine guarding and signs

☐ Are point-of-operation guards in place and working on all equipment?

☐ Are all belts and pulleys less than 2.1 meters (7 feet) from the floor guarded?

☐ Are spinning parts guarded?

☐ Are warning signs properly located? Show warning signs on the extruder, see Figure 6.10.

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