Sample Chapter 2:
Physical Description of Single-Screw Extrusion
2 Physical Description of Single-Screw Extrusion

2.1 Overall Functions of a Single-Screw Extruder

This chapter is intended to provide an overall physical understanding of the single-screw extrusion operation, including the relevant polymer properties and operating conditions. Although this chapter is quite lengthy, the reader will immediately become familiar with single-screw extrusion and develop further interests to study more details presented in the following chapters. Comprehension of the physical descriptions presented in this chapter alone may prove to be sufficiently beneficial for many readers, and help them to improve their processes and products.

Referring to Chapter 1; Fig. 1.2, an extruder is used to melt a solid polymer and deliver the molten polymer for various forming or shaping processes. The screw is the only working component of the extruder. All other components (motor, gear-box, hopper, barrel and die, etc.) merely provide the necessary support for the screw to function properly. The overall functions of an extruder are depicted below.

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Polymer solid
   ↓ Feeding
EXTRUDER → Polymer melt
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Basic functions:
- Solid conveying
- Melting
- Metering

Secondary functions:
- Mixing
- Shear refining

The feeding function of transferring the feed polymer from the hopper into the screw channel occurs outside of the screw, and it essentially does not depend on the screw design.
The screw performs three basic functions: (1) solid conveying function, (2) melting function, and (3) metering function or pumping function. The three screw functions occur simultaneously over most of the screw length and they are strongly interdependent. The geometric name of a screw section such as feeding section, shown in Chapter 1; Fig. 1.3, does not necessarily indicate the only function of the screw section. For example, the feeding section not only performs solid conveying function, but also melting and metering functions.

The screw also performs other secondary functions such as distributive mixing, dispersive mixing, and shear refining or homogenization. Distributive mixing refers to spatial rearrangement of different components, and dispersive mixing refers to reduction of component sizes as described in Chapter 2; Section 2.6.4. Shear refining refers to homogenization of polymer molecules by shearing.

A single-screw extruder is a continuous volumetric pump without back-mixing capability and without positive conveying capability. What goes into a screw first, comes out of the screw first. A polymer, as solid or melt, moves down the screw channel by the forces exerted on the polymer by the rotating screw and the stationary barrel. There is no mechanism to positively convey the polymer along the screw channel toward the die. The rotating screw grabs the polymer and tries to rotate the polymer with it. Suppose the barrel is removed from the extruder, or perfectly lubricated, such that it gives no resistance to the polymer movement. Then the polymer simply rotates with the screw at the same speed and nothing comes out of the screw. The stationary barrel gives a breaking force to the rotating polymer and makes the polymer slip slightly on the screw surface. The polymer still rotates with the screw rubbing on the barrel surface, but at a slightly lower speed than the screw, because of the slippage. The slippage of the polymer on the screw surface along the screw channel results in an output rate. A lubricated screw surface increases the output rate, but a lubricated barrel surface detrimentally reduces the output rate. It is clearly understandable why commercial screws are highly polished, and why grooved barrels in the feeding section are preferred. Although many commercial practices were developed empirically rather than based on theoretical analyses, they certainly agree with the underlying theoretical concepts.

The mechanisms inside a single-screw extruder are studied by examining the polymer cross-sections along the screw channel taken from “screw-freezing experiments”. In a screw-freezing experiment pioneered by Maddock [1], the screw is run to achieve a steady-state operation. Then, the screw is stopped and water cooling is applied on the barrel (and also on the screw if possible) to freeze the polymer inside the screw channel. The barrel is heated again to melt the polymer, and the screw is pushed out of the barrel as the polymer starts to melt on the barrel surface. Then, the solidified polymer strip is removed from the screw channel and cut at many locations to examine the cross-sections along the screw channel. Some colored pellets are mixed in the feed to visualize the melting mechanism and the flow pattern. The colored pellets retain their shapes if they remained as solid inside the solid bed before the screw stopped, but they are
sheared and become streaks inside the melt pool if they were molten before the screw stopped.

Figure 2.1 shows the cross-sections of acrylonitrile-butadiene-styrene copolymer (ABS) strip obtained from a screw-freezing experiment conducted at the Polymer Processing Technology Laboratory of the Dow Chemical Company USA. The color version of Fig. 2.1 is presented in Appendix A, and it shows the ABS cross-sections with better contrast. ABS pellets were extruded using a 63.5 mm (2.5 in) D, L/D = 21 conventional screw at 40 rpm. The three barrel zones from the hopper were set at 200, 230 and 250 °C, respectively. The output rate was 34.9 kg/hr (77 lbs/h) at 262 °C melt temperature against 7.59 MPa (1,100 psi) head pressure.

Figure 2.1 Cross-sections of ABS strip along screw channel from screw-freezing experiment (courtesy of Mark Spalding, Kun S. Hyun, and Kevin Hughes, the Dow Chemical Co. USA) (color version is presented in Appendix A)
Tadmor and Klein [2], in their book, presented many examples of screw-freezing experiments. Their Fig. 5.2 for branched low density polyethylene (BLDPE) is reproduced in this book as Fig. 2.2. BLDPE pellets were extruded using a 63.5 mm (2.5in) D, L/D = 26 conventional screw at 80 RPM. All barrel zones were set at 232 °C. The output rate was 81.5 kg/h (179.4 lbs/h) against 11.385 MPa (1,650 psi) head pressure.

Referring to Figs. 2.1 and 2.2, polymer pellets fed into a screw stay loose over the first 2–4 L/D of the screw from the hopper until they are compacted. Loose pellets drop out of the screw when the screw is removed from the barrel. The pellets are quickly compacted over the next 2–3 L/D into a tightly packed “solid bed”. The solid bed moves down the screw channel as a rigid plug, and no mixing occurs inside the solid bed. The solid bed melts mainly by rubbing on the hot barrel surface as it rotates with the screw, and a thin melt film is formed on the barrel surface. The entire barrel immediately after the feed throat is set above the melting point of the polymer, unless an intensively water-cooled barrel section is used in the feeding section. The screw surface of the first several L/D is continuously cooled by cold polymer feed in a steady-state operation. The rest of the screw also becomes hot above the melting point of the polymer because of the heat conducted from hot melt. A melt film also is formed on hot screw surface, and the solid bed becomes surrounded by melt film. The thin melt film on the barrel surface is highly sheared by rotating solid bed, and a large amount of heat is generated within the thin melt film. The thin melt film is scraped off the barrel surface and collected into a “melt pool” by the advancing flight. The melt pool is sheared and mixed as it is pumped or metered along the screw channel. The melt film on the screw surface is sheared only slightly by the slow movement of the solid bed relative to the screw, and it is not scraped off the screw surface.
The solid bed width gradually decreases and the melt pool width increases as the solid bed melts along the screw, as shown in Fig. 2.1. Melting of the solid bed is complete at about \( \frac{L}{D} = 15 \) in Fig. 2.1. The solid bed melts primarily by the heat conducted from the thin melt film on the barrel surface. The solid bed also melts on the hot screw surface and at the melt pool interface, but at a sufficiently lower rate to be ignored in comparison to the melting rate on the barrel surface. Melting occurs on the surface of the solid bed, and the interior of the solid bed remains virtually at the feed temperature along the screw. As the screw speed increases, the solid bed remains longer along the screw, as shown in Fig. 2.2, eventually reaching the end of the screw and causing poor melt quality. At high screw speeds, the solid bed and the melt pool coexist over most of
the screw length. If the solid bed breaks up into small solid pieces before melting completely, the solid pieces become mixed with the melt pool and slowly melt by the heat conducted from the surrounding hot melt. Thus “solid bed breakup” leads to nonuniform melt temperature. Melting must be completed before the end of the screw and, preferably, the last several L/D of the screw should not contain any solid, in order to achieve uniform melt temperature.

The solid bed is strong under compression, but it can easily split under tension because the pellets in the solid bed are not fused together. The continuous solid bed strip along the screw channel will split if the front part accelerates or the rear part becomes wedged. The surrounding melt under pressure will flow into the broken area of the solid bed once the solid bed splits. Figure 2.2 clearly reveals such “solid bed splitting”. The cross-sections at L/D = 16, 18.5, and also 19.5 contain only the melt without any visible solid, but the following cross-sections contain a large solid bed. Solid bed splitting causes pressure fluctuation or surging, resulting in output rate fluctuation.

Figure 2.3 is a typical segment of the solidified polymer strip in the melting section obtained from another screw-freezing experiment running ABS pellets. The color version of Fig. 2.3 is presented in Appendix A. It shows the melt pool in front of the pushing flight and the solid bed in front of the trailing flight. The solid bed is completely surrounded by a thin melt film on both the barrel surface and the screw surface. The streaks in the melt pool show a circular flow path in the melt pool. Mixing occurs in the melt pool by the circular flow. The colored pellets in the solid bed retain their shapes, and they are not mixed at all with other pellets because the solid bed moves as a solid plug without internal deformation. The streaks on the bottom surface is the direction of the solid bed movement relative to the screw surface, and they have exactly the same helix angle as the flight because the solid bed can move down only along the screw channel. The streaks on the top surface indicate the direction of the solid bed movement relative to the barrel surface, and they have a slightly greater helix angle than the flight. The small difference, about 3° in this case, is the solid conveying angle, which is described further in Chapter 4; Section 4.2.2. The conveying rate of the solid bed, which is the same as the output rate of the extruder, depends on the solid conveying angle. A zero degree solid conveying angle corresponds to a zero output rate.
The pressure inside an extruder increases along the screw. Referring to Chapter 1; Fig. 1.3, the pressure usually increases fast along the feeding section and the compression section. The pressure along the metering section increases, stays constant or decreases depending on the screw design, the die design, the screen pack, and the operating conditions. The pressure at the end of the screw, that is, the head pressure, is determined by the restrictions to the melt stream flowing through the screen pack, the adaptor, and the die. Extremely high head pressures can be developed very quickly if the melt stream is blocked, blowing up the adaptor assembly and damaging the thrust bearing/gear box. For safety, a pressure transducer or gauge, located at the end of the screw, is essential to continuously monitor the head pressure and, preferably, to automatically stop the screw when the head pressure rises to the preset level.

The melt temperature exiting the die probably has the most important influence on the processability and the product properties, and it is the most important processing variable. The melt temperature is measured by a temperature detector (thermocouple,
thermistor, or infrared sensor) immersed in the melt, usually at the adaptor located between the screw and the die. The melt temperature is difficult to measure accurately because of the heat flux between the adaptor and the temperature sensing tip, and the measured melt temperature is often incorrect (see Section 2.6.3).

2.2 Feeding Function

Referring to Chapter 1; Fig. 1.2, a polymer feed, usually in the form of pellets, drops from the hopper through the feed throat into the rotating screw. This feeding function occurs by gravity in most cases for single-screw extruders. Some feeds, such as sticky powders or recycled film flakes with a large surface to volume ratio, tend to bridge inside the hopper and do not drop freely from the hopper into the screw by gravity. Such non-free flowing feeds require a forced feeding device. A short conical screw installed inside the hopper, called a “crammer feeder”, is widely used for non-free flowing feeds. Single-screw extruders do not require starved-feeding, and they usually operate with a full hopper in a flood-feeding mode. A metered feeding device, such as a volumetric feeder or a loss-in-weight feeder, is used to control the feeding rate and to run the screw in a starved feeding mode in special situations. Many polymers react with oxygen at high temperatures during extrusion, causing undesirable oxidation, degradation, or crosslinking of the molecules. Purging of the feed at the feed throat by an inert gas like nitrogen may be necessary, especially when the screw is run in a starved feeding mode.

The feed throat is directly attached to the heated barrel, and it becomes hot. Feed materials with a low melting point stick to the wall of the feed throat, reducing the feeding rate or completely blocking the feed stream in the worst case. The feed throat must be cooled by water to avoid such feed sticking problem.

A feed stream is often made of several component materials. Even if the component materials are well blended/mixed coming into the hopper, they could segregate inside the hopper. Two different materials with the same shape but different densities, or with the same density but different shapes, readily separate upon flow. “Flow segregation” of the feed materials inside the hopper is a common problem in extrusion.

Because an extruder is a continuous pump without back mixing capability, the first condition for a successful extrusion process is to provide a consistent feeding rate into the screw from the hopper, in terms of both a constant composition and a constant weight. Extrusion problems often arise from an inconsistent feeding rate.

The feeding rate of a polymer feed is determined essentially by the physical characteristics of the feed, such as size and shape, and their distribution, controlling the bulk density (the weight divided by the apparent volume), and the internal friction between the feed constituents. The feeding rate also depends on the inherent properties of the polymer (the solid density, the external friction on the metal surface), the hopper design, and the feed throat design. The external friction of the feed on the hopper wall mainly depends
on the inherent properties of the polymer and the roughness of the hopper wall. A tiny amount of lubricant or additive, especially if it is coated on the surface of the feed, can drastically alter both the internal friction and the external friction.

Because a polymer feed, in pellet, powder, or flake form, becomes interlocked in the hopper, almost supporting its own weight, the pressure at the bottom of the hopper is very low and the feeding rate is usually independent of the amount of feed in the hopper.

The driving force in flood-feeding is gravity. The opposing forces are the centrifugal force exerted by screw rotation and the back-flow of air flowing out of the screw into the hopper through the feed throat. Feed materials contain 30–70% air by volume, and the air is squeezed out of the feed as the feed is compacted into a solid bed along the screw. Continuous flow paths from the solid bed back to the hopper are necessary for the back-flow of the air. If the flow paths are blocked, the air is entrapped in the melt. Feed forms with a large surface area per unit volume, such as powders and film regrinds, are prone to the air entrapment problem.

Unfortunately, no mathematical model is available to simulate the feeding function at present. Development of a feeding model will greatly improve the computer simulation of extruder performance.

Preferred conditions for the feed material to exhibit good feeding characteristics are:

- Small pellet size in comparison to the screw channel area
- High bulk density
- Small surface area to volume ratio
- Low internal friction between the pellets
- Low external friction on the hopper surface
- High melting point

2.3 Solid Conveying Function

2.3.1 Initial Forwarding and Compaction of Pellets

Once polymer pellets enter into the screw channel through the feed throat of an extruder, they drop to the bottom of the barrel because of gravity. The advancing flight pushes the pellets forward along the barrel as illustrated in Fig. 2.4. When the screw channel is not full under the hopper, the pellets do not make full contact with the screw surface and the screw cannot grab the pellets to rotate with it. The pellets are efficiently pushed forward by the advancing flight until the screw channel becomes full. The initial forwarding mechanism is the same as that of screw conveyors such as the grain feeders used by farmers.
The screw surface becomes hot because of the heat conducted from the melt, and the screw tip at the die end is heated to the same temperature as the melt. The screw surface under the hopper is cooled continuously by the incoming stream of cold feed pellets in a steady-state operation. Thus the screw surface in this section stays below the melting point of the pellets in a steady-state operation, and the rubbing force of the pellets on the screw surface is controlled by the external friction of the pellets. Low external friction coefficient of the pellets on the screw surface allows easy sliding of the pellets on the screw, resulting in fast forwarding and compaction. However, the barrel surface immediately after the feed throat is usually set well above the melting point of the pellets, and the rubbing force of the pellets on the barrel surface is controlled by the viscosity of the polymer. High polymer viscosity gives high rubbing force on the barrel, resulting in fast forwarding and compaction.

**Figure 2.4** Initial forwarding and compaction of pellets

The ratio of the viscosity on the barrel surface to the external friction coefficient of the polymer, \( \eta / \mu_e \), may be used as a parameter to indicate the initial forwarding and compaction characteristics of the pellets.

If the screw surface under the hopper becomes hot and pellets stick on the screw surface, the pellets stuck on the screw will rotate with the screw, reducing the screw channel area and the output rate. Then the output rate slowly decreases with time after startup. Such phenomenon is called “feed bridging”. The feed bridging problem often occurs on restart after an interrupted operation because the screw surface under the hopper becomes hot during screw stoppage. *Sticking of polymer pellets on screw surface must be avoided in the first several L/D of a screw to avoid feed bridging.* If the sticking problem occurs, the screw over the first several L/D should be bored out and cooled by water or other suitable cooling medium.

The screw channel quickly becomes full, usually after 3–5 L/D from the hopper, and the pellets start to be compacted into a solid bed, developing pressure. High internal friction between the pellets is desirable to transfer the screw torque to the pellets for compaction. Spherical pellets like ball bearings with a low internal friction slide past each other and are not compacted easily. Soft pellets are compacted easily along the screw. Harder pellets
are more difficult to compact, and full compaction is achieved farther away from the hopper. The air between the pellets also goes into the screw with the pellets. It is remarkable that all the air is squeezed out of the screw as the pellets are compacted. There must be continuous flow paths for the air to flow backward from the compacting solid bed to the hopper. If the flow paths are blocked by penetrating melt, the air becomes entrapped in the melt and the entrapped air mixed in the melt is extruded. The air entrapment problem is common for hard polymers and powder feeds. The initial forwarding and compaction rate of a screw usually increases proportional to the screw speed. At present, there is no mathematical model that can be used to predict the forwarding and compaction rate. Preferred conditions for a high rate of the initial forwarding and compaction are:

- High rubbing force on the barrel
  - High viscosity of the polymer
  - Barrel temperature near the melting point of the polymer
  - Grooved barrel surface
- Low rubbing force on the screw
  - Low external friction coefficient of the polymer
  - Low screw surface temperature far below the melting point of the polymer
  - Polished screw surface
  - Low friction coating on the screw surface
- High melting point
- High bulk density
- Soft pellets for easy compaction
- Shape and size favorable for high internal friction

### 2.3.2 Solid Bed Conveying

Polymer pellets inside a screw channel are compacted into a solid bed (or a solid plug) after 3–5 L/D from the hopper by the pushing force of the screw, as discussed in the previous section. For most polymers which are rigid at the feed temperature, the solid bed moves down the screw channel as a rigid body. Once the solid bed is fully compacted after 5–7 L/D, it is very strong under compression, like a rock, and it cannot be easily compressed or sheared. But, it can be easily split or broken up by tensile force because the pellets in the solid bed are not fused together. It will be important to remember various solid bed characteristics when the screw mechanisms are studied later, in more detail.
Figure 2.5 shows that the solid bed makes direct contact with the surrounding barrel and screw surfaces. This case occurs if the barrel and screw surfaces are kept below the melting point of the polymer. However, the entire barrel, starting from the first zone next to the hopper, is usually heated well above the melting point of the polymer. The screw also becomes hot because of the heat conducted from the melt. The tip of the screw reaches the melt temperature unless the screw is bored to the tip and cooled. The screw temperature increases quickly along the screw and reaches the melting point after 5–7 L/D from the hopper. Thus the screw temperature, where the solid bed is formed, is usually well above the melting point. Because a polymer melts quickly upon touching a hot metal surface above its melting point, the solid bed melts on all barrel and screw surfaces. The solid bed becomes surrounded by the melt, as shown in Fig. 2.6. Figs. 2.5 and 2.6 represent two limiting situations. The solid bed, in real situations, goes through transition stages from Fig. 2.5 to Fig. 2.6.

The rotating screw grabs the solid bed and makes the solid bed rotate with it. As the rotating solid bed rubs on the stationary barrel, the barrel exerts a breaking force on the solid bed and makes the solid bed slide slightly on the screw surface. Therefore, the solid bed rotates at a slightly lower speed than the screw. If the barrel is removed or lubricated, the solid bed rotates with the screw at the same speed. The difference between the rotational speeds of the screw and the solid bed results in the solid conveying rate according to the helical geometry of the screw channel.

Figure 2.5  Solid bed in direct contact with barrel and screw

Figure 2.6  Solid bed surrounded by polymer melt

The slippage of the solid bed on the screw, that is, the solid bed conveying rate down the screw channel is controlled by the difference between two forces exerted on the solid bed by
the rotating screw and the stationary barrel. The pressure inside the screw channel usually increases along the screw because the forwarding force accumulates along the screw. The increased pressure along the screw channel pushes the solid bed backward toward the hopper. The only driving force for solid bed conveying is the rubbing force exerted on the solid bed by the stationary barrel, resisting the solid bed rotation. The opposing forces are the rubbing force exerted on the solid bed by the rotating screw and the increased pressure along the screw channel. A high rubbing force on the barrel and a low rubbing force on the screw are desirable for a high solid conveying rate. It is common practice to highly polish the screw surface in order to minimize the rubbing force on the screw. The barrel surface near the hopper can be grooved and/or cooled by water to increase the rubbing force on the barrel.

The rubbing force on the barrel or screw surface may be frictional or viscous in nature, depending on the temperature condition of the metal surface. If the metal surface is at a temperature above the melting point of the polymer, the polymer melts as shown in Fig. 2.6, and the rubbing force is viscous in nature. Because the first barrel zone temperature next to the hopper is usually set well above the melting point of the polymer in most cases, the rubbing force on the barrel is viscous in nature and the pressure builds up linearly along the screw channel, as discussed in Chapter 4. A polymer with a high viscosity gives a high solid conveying rate in this case.

If the metal surface is at a temperature below the melting point of the polymer, the solid bed does not melt, as shown in Fig. 2.5, and the rubbing force is frictional in nature. The barrel is readily heated above the melting point of the polymer in operation by the heat generated from the frictional force of the solid bed unless it is cooled efficiently. The barrel section next to the hopper may be grooved and intensely water-cooled, in order to keep the barrel surface below the melting point of the polymer. Then, the rubbing force on the barrel is frictional in nature and the pressure increases exponentially along the screw channel, as discussed in Chapter 4. Extremely high internal pressures over 69 MPa (10,000 psi) can be developed in this case. However, a grooved barrel without intense water-cooling does not keep the barrel surface below the melting point of the polymer, and such high pressures are not developed. Even if water-cooling is not applied, a grooved barrel increases the solid conveying rate by increasing the rubbing force on the barrel [3].

Elastomeric polymers with a low melting or fusion temperature, such as thermoplastic elastomers, present a unique solid conveying problem. The pellets of these polymers can fuse together upon compression, forming an elastic band in the feeding section. The elastic band stretches by screw rotation and the stretched elastic band wraps around the screw, tightly holding onto the screw and thus stopping solid conveying. If such a "feed binding" problem occurs, the output rate is very low and increases only slightly with increasing screw speed.

The mass solid conveying rate of a screw is equal to \[ \text{(the sliding velocity of the solid bed on the screw surface)} \times \text{(the screw channel cross-sectional area perpendicular to the screw flight)} \times \text{(the bulk density of the solid bed)} \]. The mathematical solid conveying
models presented in Chapter 4 are used to calculate the solid conveying rate. The solid conveying rate usually increases nearly proportional to the screw speed. The mass output rate of an extruder is equal to the mass solid conveying rate, because an extruder is a continuous pump.

Preferred conditions for a high conveying rate of the solid bed are:

- Large screw channel area
- High rubbing force on the barrel
  - High viscosity of the polymer
  - Barrel temperature near the melting point of the polymer
  - Grooved barrel surface
- Low rubbing force on the screw
  - Screw temperature significantly higher than the melting point of the polymer
  - Highly polished screw surface
  - Low friction coating on the screw surface
- Small screw surface area in comparison to the barrel area
  - Low screw channel depth to width ratio
  - Large flight radius on the screw root
- Low pressure increase along the screw channel
  - Long feeding section
  - No or low reduction of the channel area along the screw

### 2.4 Melting Function

Polymers have a very low thermal conductivity attested by their usage as thermal insulators. Unless an internal heat generation method such as dielectric or microwave heating is used, heat must conduct from the surface into the center of a solid bed to melt the solid bed. Because of the low thermal conductivity, the solid bed melts very slowly. The melting capacity of a screw increases less than proportional to screw speed, mainly because the dwell or residence time of the solid bed inside the screw decreases as screw speed increases. The melting capacity eventually becomes the limiting factor in the output rate as screw speed increases. Some pellets in the solid bed eventually become incompletely molten at the end of the screw at high screw speeds, resulting in poor melt quality. Most high performance screws are designed to eliminate incompletely molten pellets and to increase the melting capacity.
The melting capacity of a screw may be calculated by the mathematical models presented in Chapter 4. All calculations for complex engineering problems are approximations. This statement is particularly true for the complex melting capacity calculations. The predictions of the complex melting models are, at best, only approximations, because of many mathematical simplifications used to develop the models and many approximate polymer properties used in the calculations.

2.4.1 Dissipative Melting

The solid bed starts to melt instantly on contacting the hot barrel surface. Referring to Figs. 2.1 to 2.3, the solid bed also melts on the hot screw surface. However, the melting mechanism on the screw surface is inefficient, because the melt formed on the screw surface is not scraped off. The solid bed melts and forms a thin melt film on the barrel surface as it is rubbed on the hot barrel surface. The melt film on the barrel surface is scraped off and collected into a melt pool by the advancing screw flight. The solid bed and the melt pool are conveyed along the screw channel. Therefore, the screw channel performs all three solid conveying, melting, and metering functions simultaneously during the melting stage.

The solid bed rotates with the screw at almost the same speed as the screw. The melt film between the solid bed and the barrel is highly sheared by the rubbing motion of the solid bed on the barrel surface as the solid bed rotates with the screw. Because polymer melts have a high viscosity, a large amount of heat is generated within the melt film by dissipating the mechanical power of the drive motor. It is noted that viscosity comes from the internal friction between molecules, which converts mechanical energy into thermal energy. The melt film conducts heat into the solid bed, melting the solid bed at the melt film-solid bed interface. Such a melting mechanism, shown in Fig. 2.7a (color version in Appendix A), is called “dissipative melting”. The melt film also exchanges heat with the barrel by conduction. The melt film usually receives heat from the barrel at low screw speeds, and higher barrel temperatures give higher melting rates at low screw speeds. However, the melt film becomes hotter than the barrel by internally generated heat at high screw speeds. The barrel becomes overheated and must be cooled to maintain the set point and to avoid overheating the polymer at high screw speeds. The screw speed and thus the output rate are often limited because the melt film temperature becomes undesirably high at high screw speeds.

A tight flight clearance (the gap between the flight and the barrel surface) is desirable in order to scrape the melt film off the barrel surface as completely as possible. Residual melt film left on the barrel by a large flight clearance reduces the melting capacity. Frequent scraping of the melt film off the barrel surface by the flight promotes melting by making the melt film thinner. At a given screw speed, the shear rate inside a melt film increases and more heat is generated as the melt film thickness decreases. As the melt film becomes hotter, more heat flows from the melt film into the solid bed, resulting in higher melting
rate. The solid bed width increases proportional to the screw diameter. At an equivalent screw peripheral speed, the scraping frequency of the flight decreases and the melt film thickness increases as the screw diameter increases. Thus the melting rate per unit barrel surface area at an equivalent screw peripheral speed decreases as the screw diameter increases. This is the main reason for poor quality melt often experienced in scale-up. Multiple-flights instead of a single-flight may be used for large diameter screws to alleviate such problem and also to reduce screw wear, but multiple-flights also have adverse effects because they reduce the channel area and generate more heat over the flights.

Preferred conditions for a high dissipative melting capacity of a screw at a given screw speed are:

- High barrel temperature well above the melting point of the polymer
- Large solid bed-barrel contact area
- Small channel width
- Tight flight clearance
- High feed temperature
- High polymer viscosity for large amount of heat generation
- Low melting point
- Low heat capacity for melting
2.4.2 Conduction Melting

As the solid bed continues to melt along the screw channel, the solid bed area decreases and the melt pool area increases, as shown in Figs. 2.1 and 2.2. When the solid bed becomes small, it cannot maintain its integrity against various forces acting on it and it breaks up into pieces. This phenomenon is called “solid bed breakup”. Careful examination of Fig. 2.2 reveals that the solid bed breakup occurred at about L/D = 20. The broken solid bed pieces are mixed in the melt, as seen in the cross-sections over L/D = 20 – 26. The solid bed pieces mixed in the melt must melt by the heat conducted from the surrounding hot melt. Such a melting mechanism, depicted in Fig. 2.7b (color version in Appendix A), is called “conduction melting”. Conduction melting is a slow process because of the very low thermal conductivity of polymers. Large solid bed pieces take long times to melt and eventually become incompletely molten, even at the end of screw as screw speed is increased, causing poor melt quality. Barrel heating has little effect on the conduction melting of the broken solid bed pieces. The most important factor for conduction melting is the size of solid pieces. The time necessary to completely melt a solid piece immersed in a hot melt increases exponentially with the size of the solid piece. Therefore, the size of the broken solid bed pieces must be minimized by a good screw design for fast conduction melting. The individual feed pellets are the smallest solid pieces after solid bed breakup. Good mixing of the solid pieces and the melt increases the heat transfer, resulting in faster melting.

Preferred conditions for fast conduction melting are:

- Small pellet size with large surface area
- Good mixing of the melt and the solid pieces
- High feed temperature
- Low melting point
- Small heat capacity for melting

2.5 Metering Function

When all pellets are molten toward the end of a screw, the rest of the screw functions as a metering pump to pump the polymer melt out of the screw through the die. As the screw rotates, some of the melt adheres on the screw and rotates with the screw. Some of the melt is held back or dragged by the stationary barrel and comes out of the screw because of the helical geometry of the screw channel. Because the movement of the melt rotating with the screw is difficult to visualize, it is customary to assume that the screw is stationary and the barrel rotates in the opposite direction of the screw rotation. In this way, the movement of the melt relative to the screw can be easily observed through a transparent barrel. Figure 2.8 shows a stationary unwrapped rectangular screw channel with a moving
barrel. The forward flow caused by the drag of the moving barrel is called the “drag flow”. The drag flow, without the adverse effects of the flights, is 50% of the channel volume in one wrap per each screw rotation. However, the melt adheres on the pushing flight and the trailing flight, significantly reducing the drag flow. Because the pressure usually increases toward the die, the pressure drop toward the hopper causes the melt to flow backward toward the hopper. The backward flow caused by the pressure drop is called the “pressure flow”. The metering rate is determined by the interaction of the drag flow and the pressure flow. If the pressure drop is zero, the metering rate is equal to the drag flow rate.

Referring to Fig. 2.8a, movement of the barrel relative to the screw can be resolved into two components: one along the screw channel parallel to the flight and the other across the screw channel perpendicular to the flight. The drag flow caused by the barrel movement can be resolved into two components, corresponding to the two components of the barrel movement; one along the screw channel called the “down-channel drag flow”, shown in Fig. 2.8b, and the other across the screw channel called the “cross-channel drag flow” or the “transverse flow”, shown in Fig. 2.8c. The transverse flow makes the melt run into the flights. The melt flowing toward the pushing flight near the barrel surface must flow downward along the pushing flight toward the screw root, flow across the screw channel along the screw root back to the trailing flight, and then flow upward along the trailing flight, making a circular path. The pressure flow, shown in Fig. 2.8d, has one flow component along the screw channel toward the feed. The interactions between the down-channel drag flow, the transverse flow, and the pressure flow produce the final complex helical flow pattern inside the screw channel, as shown in Fig. 2.8e. The helical flow pattern resembles a twisted rope made of many parallel fibers. The melt near the center of the screw channel has the minimum transverse flow and goes through the screw channel fastest, receiving little mixing action. The melt near the outside of the screw channel has the maximum transverse flow and goes through the screw channel slowest, receiving the maximum mixing action.

Analysis of a screw pump is an easy problem for simple fluids like water. The difficulty involved in predicting the metering rate of a screw for a polymer melt arises from the strong dependence of melt viscosity on shear rate as well as temperature. Furthermore, the temperature is not uniform within the melt because of the heat generation within the melt and the heat conduction with the barrel. The simplest method of calculating the metering rate assumes that the melt temperature is uniform and the polymer melt viscosity is independent of shear rate. This simplest case corresponds to an isothermal Newtonian fluid, and the metering rate becomes

\[ \text{Metering rate} = \text{Drag flow rate} - \text{Pressure flow rate} \]
The details of this simple method and other advanced methods are presented in Chapter 4. The metering rate is relatively simple to calculate in comparison to the solid conveying rate or the melting rate. The metering rate can be calculated quite accurately, and it is the most important calculation because it is equal to the output rate. Metering rate increases somewhat less than proportional to screw speed in most operations.

Flight clearance reduces the metering rate because the melt inside the flight clearance is not scraped off the barrel by the flight, and also the pressure differential across the flight makes the melt to leak over the flight through the flight clearance. For simplicity, the percent reduction in the metering rate caused by the flight clearance may be equated to the percentage of the flight clearance relative to the metering channel depth from the screw root to the barrel surface. Because the nominal flight clearance of a new screw is about 0.1% of the screw diameter and only a few percent of the metering channel depth, it can be safely neglected in comparison to the expected accuracy of the calculation. The effect of flight clearance on the metering capacity is not as great as its effect on the melting capacity.

Figure 2.8 Unwrapped stationary rectangular screw channel with moving barrel, and flow pattern of melt relative to screw: (a) Separation of the barrel velocity into the down-channel and the cross-channel components; (b) Down-channel drag flow; (c) Cross-channel drag or transverse flow; (d) Pressure flow; (e) Combined helical flow path
Preferred conditions for a high metering rate are:

- Large screw channel area
- Small flight surface areas in comparison to the barrel area
  - Low channel depth to width ratio
- Low pressure increase or high pressure decrease along the metering section
  - Long metering section
  - High pressure at the start of the metering section
  - Low head pressure (low pressure drop through the screen pack, adaptor and die)
- Tight flight clearance
- High polymer viscosity

2.6 Melt Quality and Melt Stability

2.6.1 Definition of Melt Quality and Melt Stability

The performance of an extruder is judged not only by the output rate, but also by the melt quality and the melt stability. The melt quality and the melt stability directly control the quality and dimensional stability of the product. The melt quality can be quantitatively judged by the following measurements:

- Closeness of the melt temperature to the desired level
- Melt temperature distribution across the melt stream measured at a given time
- Degree and uniformity of mixing across the melt stream
- Residence time distribution

The melt stability refers to the steadiness of melt quality and the stability of melt pressure with time, and it can be quantitatively judged by the following measurements:

- Melt temperature fluctuation with time measured at a given location
- Variation in the degree of mixing with time measured at a given location
- Melt pressure fluctuation with time measured at a given location

The melt temperature and the melt pressure are continuously measured usually at the adaptor connecting the extruder to the die, as shown in Fig. 2.9. Figure 2.10 is an example of such measurements. Melt temperature and melt pressure usually change in the opposite directions, as shown in Fig. 2.10. A melt temperature sensor (thermocouple or other type of temperature detector) with its sensing tip shielded by a metal is often used in production because of its mechanical strength. However, it measures the adaptor wall temperature...
rather than the melt temperature because of the high thermal conductivity of the shielding metal. For accurate melt temperature measurements, a melt temperature sensor with its sensing tip exposed and insulated from the casing metal should be used. The sensing tip is immersed into the melt stream at variable depths to measure the melt temperature distribution across the melt stream. The degree of mixing is usually measured off-line, using microscopes. Residence time distribution is difficult to measure, involving a tracer material such as a pigment or an active filler.

![Temperature sensor](image1)

*Figure 2.9* Melt temperature and melt pressure measurements at adaptor

![Temperature sensor](image2)

*Figure 2.10* Melt temperature and melt pressure recordings with time

### 2.6.2 Melt Pressure

The melt pressure can be accurately measured by a pressure transducer, and it is independent of the sensing tip (usually a metal diaphragm) immersion depth into the melt stream. The melt pressure level at the adaptor depends on the viscosity of the
polymer, the die design, and the output rate. It does not depend on the screen pack or the melt quality. Higher melt pressure gives a lower output rate at a given screw speed, resulting in a higher melt temperature, but improves mixing and melt pressure stability. Thus the melt pressure level indirectly influences the melt quality. Referring to Fig. 2.10, the fluctuation of the melt pressure over a short time period on the order of second is called “surging”. Surging indicates fast fluctuations in the output rate, and it gives dimensional variations of the products in continuous extrusion processes. Surging is a difficult problem to eliminate. Surging usually cannot be eliminated by controlling the operating conditions and requires appropriate changes in the screw design to solve the problem. Recalling that a single-screw extruder is not a positive pump and the movement of the polymer inside the screw channel is determined by the delicate balance of several fluctuating forces acting on the polymer, it should not be surprising to observe surging. When the pressure inside a screw is measured at several locations along the screw, a large magnitude of surging is observed in the feeding section. The surging propagates along the screw toward the die like ocean waves, and its magnitude decreases as the pressure builds up along the screw. The magnitude of surging measured at the adaptor usually does not change with the melt pressure level. A reasonably high melt pressure level is desirable because it results in a low percent surging. Percent surging is the ratio of the magnitude of surging to the melt pressure level. The minimum level of percent surging achievable with single-screw extruders is usually about $\pm 1.0\%$. A gear pump, described in Chapter 6, is necessary to achieve better melt pressure stability. Higher screw speeds and larger diameter screws lead to more melt pressure fluctuation.

An inconsistent feeding rate obviously causes surging as well as fluctuations in melt temperature and mixing. A consistent feeding rate is the essential requirement to ensure stable extrusion, and it will be implicit in any stability discussion. Any imbalance in the solid conveying, melting, and metering rates, such as excessive metering rate caused by very deep metering depth or insufficient solid conveying rate caused by very shallow feeding depth, results in surging. Solid bed splitting or breakup results in nonuniform melt temperature in the melt stream, leading to surging. Another common cause for surging is an excessive reduction rate of the channel area in the compression section. Referring to Chapter 1; Fig. 1.3, the compression ratio (CR) is approximated by the ratio of the channel depths of the feeding section to the metering section if the channel width stays constant. The reduction rate of channel area can be represented by the CR divided by the length of the compression section. The solid bed, moving from the feeding section to the metering section, must pass through the progressively decreasing channel area of the compression section. If the reduction rate of the channel area is more than the melting rate of the solid bed, then the hard solid bed is compressed and becomes wedged in the screw channel until it melts sufficiently to pass through the reduced channel area. One of the most important screw design parameters is the reduction rate of the channel area along the compression section. The CR by itself does not describe the reduction rate of the channel area. The CR is important, but it must be considered together with the length of the compression section.
The change in the melt pressure level over a long time period, on the order of minute, is called “melt pressure drift”. Melt pressure drift causes a slow change in the output rate with time. Melt pressure drift is usually caused by the screen pack being contaminated, or slowly changing feeding condition, barrel temperature, or screw temperature. Feed bridging under the hopper is another cause for slow downward melt pressure drift after startup. Melt pressure drift may be eliminated by a feedback control scheme of automatically changing the screw speed to maintain a constant melt pressure at a location past the screen pack.

2.6.3 Melt Temperature

The melt temperature is measured by thermocouple, thermistor, infrared sensor, or other type of temperature detector. Unlike the melt pressure, the melt temperature is quite difficult to measure accurately. The measured melt temperature is strongly influenced by the adaptor wall temperature because of high thermal conduction between the adaptor and the sensing tip through the protective shielding metal covering the sensing tip. Because the adaptor is usually set at a temperature substantially below the melt temperature to avoid sticking or burning of the melt on the adaptor wall, the measured melt temperature is often significantly lower than the actual value. A thermocouple with a sensing tip exposed and insulated from its body must be used to measure the melt temperature accurately. Figure 2.10 shows two kinds of melt temperature variations with time, the fluctuation over a short time period on the order of second, called “melt temperature fluctuation”, and the slow change over a long time period, called “melt temperature drift”. The thermocouple and the recorder must have a fast response time in order to detect the true magnitude of fast melt temperature fluctuation without damping. Melt temperature fluctuation is associated with surging, and melt temperature drift is associated with melt pressure drift. The causes for melt temperature fluctuation and melt temperature drift are the same as those for surging and melt pressure drift, respectively, discussed in the previous section.

Solid bed splitting or breakup obviously leads to melt temperature fluctuation. Uneven melt temperature inside the screw channel gives melt temperature variation across the melt stream and also melt temperature fluctuation at a given position in the melt stream. Polymer melt exits from the screw channel as a strip. The temperature of the melt strip is nonuniform across its cross-section. Because the barrel section near the die end usually is cooled, the surface of the melt strip, which was previously in contact with the barrel, is at a lower temperature than the center. The melt strip becomes a helical coil because of screw rotation, as illustrated in Fig. 2.11, and the helical coil is compressed into a circular rod with non-uniform temperature distribution inside the adaptor. A temperature sensing tip located at a given position inside the adaptor is exposed to different spots of the melt strip with different temperatures as the helically wound melt strip flows over the sensing tip. The minimum melt temperature fluctuation achievable in single-screw
extruders is about ± 2 °C. Higher screw speeds and larger diameter screws give more melt temperature fluctuation.

The melt temperature across the melt stream in the adaptor is not uniform, as can be deduced from Fig. 2.11. Therefore, the measured melt temperature depends on the position of the sensing tip in the melt stream. Figure 2.12 shows a typical melt temperature distribution across a circular adaptor. The melt temperature near the adaptor wall is low because the adaptor is set at a low temperature in most cases. Again, referring to Fig. 2.11, the melt flowing near the adaptor center has a lower temperature because it corresponds to the outside of the melt strip, which was in contact with the cooled barrel. The highest melt temperature is detected at a point about 40–60% of the radius into the adaptor from the adaptor wall.

![Flow pattern of melt from screw into adaptor](image1)

**Figure 2.11** Flow pattern of melt from screw into adaptor

![Typical melt temperature distribution across circular adaptor](image2)

**Figure 2.12** Typical melt temperature distribution across circular adaptor

It will be clear from the preceding discussion that the average melt temperature is very difficult to measure. Melt temperatures reported by different plants or measured in different ways on the same line cannot be compared. The measured melt temperature most likely is not the average melt temperature. The specific energy consumption calculated by dividing the screw power consumption by the output rate is a good indication of the average melt temperature. The average melt temperature always increases with increasing screw speed because the screw power consumption increases more than proportional to screw speed, whereas the output rate increases less than proportional to screw speed within the operating range of screw speed.
2.6.4 Mixing

When a polymer melt is mixed with an immiscible additional component, the polymer melt becomes the continuous phase or the matrix of the compound and the additional component becomes the dispersed phase forming discrete domains imbedded in the matrix.

There are two types of mixing: (1) distributive mixing and (2) dispersive mixing (or dispersion), as illustrated in Fig. 2.13a. Distributive mixing refers to uniform distribution of different components in space, and it does not require a high stress. Dispersive mixing refers to reduction of the component size, and it occurs only when the stress in the melt exceeds the coherent strength of the component. In reality, distributive mixing involves some dispersive mixing, and dispersive mixing involves some distributive mixing.

If the dispersed phase is an immiscible liquid, the shape of the resulting domains may be spherical, cylindrical, or lamellar depending on the volume fraction, viscosity, elasticity, and compatibility of the dispersed phase as well as the intensity and type of mixing. A typical deformation and breakup of a liquid domain are illustrated in Figure 2.13b. Liquid domains break up easier and become smaller when the viscosity of the liquid domains is lower than the viscosity of the polymer melt. For an example, consider mixing of oil and grease. Oil added into grease is easily sheared into small domains upon mixing, but grease added into oil does not easily breakup.

If a polymer melt is mixed with a miscible additional component, intermolecular diffusion occurs on the molecular level as shown in Figure 2.13c in addition to distribution and dispersion. The smaller molecules of the additional component in the dispersed phase diffuse into the polymer matrix. The larger polymer molecules also diffuse into the dispersed phase at a much slower rate. The mixture eventually becomes a single phase with a uniform composition. Such intermolecular diffusion occurs at the interfaces of the polymer matrix and the dispersed phase, and the interfacial area increases with decreasing size of the dispersed phase. The rate of intermolecular diffusion increases exponentially with increasing temperature, but virtually does not depend on the stress or the flow rate. The time to reach the final uniform composition decreases exponentially with increasing temperature or increasing the interfacial area.
The degree and uniformity of mixing achieved through an extruder are usually measured by adding a small amount of pigment or filler in the feed stream. The extrudate exiting the die is pressed into a thin film, and an optical microscope is used to observe the distribution and the sizes of the pigment or the filler particles in the film. Different parts of the extrudate are examined for the uniformity of mixing. Different parts of the extrudate receive different amounts of work through the screw, attaining different degrees of mixing. Mixing is obviously important if there are more than one component in the feed. Although it is not obvious, mixing is also important even for a single component polymer feed because the properties of many polymers change with the degree of shearing.

Single-screw extruders do not provide efficient mixing. Because a solid bed moves as a rigid body, mixing does not occur inside the solid bed. Mixing through single-screw extruders is accomplished only by the shearing action of polymer melt exerted by the screw. Distributive mixing results from different velocities of the melt at different locations. Referring to Fig. 2.8, distributive mixing occurs inside the melt because of the helical flow paths within the melt. Splitting and shuffling of the melt stream result in good
distributive mixing. High stresses are developed in the melt film over the solid bed, and the maximum dispersive mixing occurs in the melt film during the dissipative melting process of the solid bed. A solid bed made of pellets develops a higher stress in the melt film than a solid bed made of powders. Therefore, better dispersive mixing is achieved with pellets than powders. A high stress is also developed in the melt over the flight, and dispersive mixing occurs in the clearance over the flight.

Unique mixing devices have been developed to improve mixing in single-screw extruders. Some of these mixers are presented in Chapter 6. Static mixers, which are placed inside the adaptor between the screw and the die, do not have any moving part. Static mixers give good distributive mixing by splitting and shuffling the melt stream, but they are ineffective in dispersive mixing because they do not develop a high stress. Dynamic mixers have a moving part driven by the screw. Dynamic mixers, because of the actions of the moving part, can develop a high stress, as well as splitting and shuffling the melt stream. Thus dynamic mixers give better dispersive mixing than static mixers, as well as good distributive mixing.

2.6.5 Effective Residence Time and Residence Time Distribution

The duration of time that a polymer stays inside an extruder is the residence time or the dwell time. The average residence time of the polymer through the extruder is equal to the total channel volume divided by the volumetric output rate. However, the duration that the polymer stays inside an extruder as solid inside the solid bed is not important because physical change such as mixing and chemical change such as degradation or crosslinking do not occur in the solid polymer. The duration that the polymer stays inside an extruder as a physically and chemically active hot melt is the important residence time, and such duration will be called the “effective residence time”. The pellets molten near the hopper have a long effective residence time, and the pellets molten near the die have a short effective residence time.

Polymer pellets molten at the same location along a screw have different residence times through the rest of the screw because different parts of the melt inside the screw channel have different down-channel velocities, as shown in Fig. 2.8. The residence time distribution depends on the flow pattern and mixing inside the screw channel. Uniform down-channel velocity and good mixing across the entire cross-sectional area of the screw channel give a narrow residence time distribution.

All pellets in the solid bed move along the screw channel at the same down-channel velocity as a rigid body. The motion of a rigid body is called “plug flow”. Referring to Fig. 2.14a, all parts of a rigid body in plug flow have the same residence time with zero residence time distribution. The flow of a fluid through a circular tube gives a very broad residence time distribution. The residence time distribution of a polymer through a single-screw melt extruder is not as broad as that of the tube flow because of the mixing action of the cross-
channel flow ([4]; p.457). The residence time distribution through an intermeshing twin-screw melt extruder is narrower than that of a single-screw extruder because of the self-cleaning action and better mixing capability. A melt extruder refers to a melt-fed extruder, and it simply acts as a melt pump. For a melt extruder, the residence time is the same as the effective residence time. Figure 2.14b compares the effective residence time distribution of a solid-fed, single-screw extruder to a melt-fed, single-screw extruder.

![Figure 2.14](image)

2.7 Thermodynamic Analysis of Polymer Extrusion

The energy balance for a polymer extrusion operation is illustrated in Fig. 2.15. The first law of thermodynamics, that is, the conservation of energy, must be satisfied. The energy necessary for the polymer extrusion operation is provided by the motor and the barrel heaters. A very small, usually negligible, portion of the motor energy is lost through the drive chain as frictional heat in the coupling and the gear box. Most of the mechanical
Thermodynamic Analysis of Polymer Extrusion

Energy ($W_o$) of the motor consumed to rotate the screw is converted into heat by shearing the polymer melt. A large amount of heat is generated in the melt by viscous dissipation as the melt is sheared by screw rotation. A very small portion of the mechanical energy is used to compact the polymer feed, to develop the melt pressure, and to meter the melt out of the screw. The melt pressure developed at the end of the screw drops to ambient pressure as the melt comes out of the die, converting the mechanical energy associated with the melt pressure into heat. Virtually the entire mechanical energy of the motor is converted into heat. The heat generated in the melt is the main source of heat used to melt the polymer feed. The heat or thermal energy ($Q_o$) provided by the barrel heaters conducts to the polymer through the barrel. When the melt overheats above the set point of the barrel heater, the cooling system on the barrel takes away heat ($Q_c$) from the melt. A substantial amount of heat ($Q_l$) is lost to the ambient through the barrel and the screw shaft. The balance of the total mechanical and thermal energies is equal to the increased heat content of the polymer from the feed temperature to the melt temperature.

Referring to Fig. 2.15, the extruder takes the solid polymer at temperature $T_1$ and pressure $P_1$ with enthalpy $H_1$, and extrudes the molten polymer at $T_2$ and $P_2$ with $H_2$. It is noted that enthalpy is a function of both temperature and pressure. At a constant temperature, enthalpy increases with increasing pressure.

The energy balance for unit polymer mass going through the extruder is given by the first law of thermodynamics.

$$
\Delta H + \Delta PE + \Delta KE = \Delta Q + \Delta W
$$

where

- $\Delta H = H_2 - H_1$ = enthalpy increase per unit polymer mass
- $\Delta PE$ = potential energy increase per unit polymer mass
- $\Delta KE$ = kinetic energy increase per unit polymer mass
- $\Delta Q$ = net thermal energy input into unit polymer mass
- $\Delta W$ = net mechanical energy input into unit polymer mass

Because $\Delta PE$ and $\Delta KE$ are negligible in comparison to $\Delta H$ in extrusion, Eq. 2.1 reduces to

$$
\Delta H = \Delta Q + \Delta W
$$

Referring to Fig. 2.15, $\Delta Q$ and $\Delta W$ can be expressed as

$$
\Delta Q = (Q_o - Q_c - Q_l)/G
$$

$$
\Delta W = W_o/G \text{ neglecting mechanical losses}
$$
Combining Eqs. 2.2, 2.3 and 2.4, the required motor power is obtained.

\[ W_o = G \cdot \Delta H - (Q_o - Q_c - Q_l) \]  

(2.5)

Adiabatic operation refers to no heat exchange between the extruder and the surrounding such that \( \Delta Q = (Q_o - Q_c - Q_l) = 0 \). The theoretical motor power in the adiabatic operation is

\[ W_o^* = G \cdot \Delta H \]  

(2.6)

where \( W_o^* \) = theoretical motor power in the adiabatic operation

Most modern extruders running at high screw speeds generate excessive heat and utilize barrel cooling. Therefore, the motor power of an extruder must be substantially more than the value predicted by Eq. 2.6. The mechanical energy efficiency of an extruder is defined by the ratio of the theoretical motor power in the adiabatic operation, \( W_o^* \), to the actual motor power consumed in the operation, \( W_o \):

\[ \% \text{ Mechanical energy efficiency} = 100 \cdot \left[ \frac{(W_o^*)}{(W_o)} \right] \]  

(2.7)
Thus the minimum motor power of the extruder should be

\[ W_o = \left( \frac{W_o^*}{100}\right) \left[ \% \text{ Mechanical energy efficiency} \right] \]  

It is common practice to express the mechanical energy efficiency by either the polymer output produced by unit motor power consumption, \((G / W_o)\), in terms of \([\text{kg}/(\text{kW-h})]\) or \([\text{lb}/(\text{HP-h})]\), or, inversely, the motor power consumed to produce unit polymer output, \((W_o/G)\), in terms of \([(\text{kW-h})/\text{kg}]\) or \([(\text{HP-h})/\text{lb}]\). The following symbols and unit conversion factors are used in the discussion. Appendix B lists other unit conversion factors relating metric units, British units, and SI units.

- 1.0 lb (pound) = 0.4536 kg (kilogram)
- 1.0 HP (horsepower) = 0.746 kW (kilowatt)
- 1.0 HP-h (horsepower-hour) = 2,544 Btu (British thermal unit)
- 1.0 kW-h = 3,600 kJ (kiloJoule) = 860 kcal (kilocalorie)

Adiabatic operation gives the maximum mechanical energy efficiency at high screw speeds, consuming the minimum motor power expressed by Eq. 2.6. Polymers require about 95–165 kcal/kg (about 170–300 Btu/lb) to be heated from room temperature to a desired melt temperature of about 175–300 °C (350–570 °F). Thus the maximum mechanical energy efficiency ranges from about 5 to 9 kg/(kW-h) or about 8 to 15 lbs/(HP-h). Actual mechanical energy efficiencies of modern extrusion operations at high screw speeds are substantially lower than the above values by as much as 40%. Mechanical energy efficiencies at low screw speeds can be higher than the above values because barrel heaters add heat to polymers. Mechanical energy efficiency always decreases with increasing screw speed because more heat is generated in the melt and less heat is conducted from the barrel heaters to the polymer. A polymer with a higher heat content naturally has a lower mechanical energy efficiency. Crystalline polymers usually have higher heat contents than amorphous polymers, and they have lower mechanical energy efficiencies than amorphous polymers.

Again, referring to Fig. 2.15, the melt pressure at the end of a screw, that is, the head pressure \(P_h\), is in the range of 50 to 400 atm (5.1 – 40.6 MPa or 735 – 5,880 psi). The melt pressure drops to \(P_2 = 0\) as the melt is extruded into ambient through the die. If there is no heat exchange between the melt and the die, the enthalpy of the melt at the head, \(H_h\) at \(T_h\) and \(P_h\), should be equal to the enthalpy of the melt exiting the die, \(H_2\) at \(T_2\) and \(P_2\). The pressure drop through the die from \(P_h\) to \(P_2\) is converted into heat, raising the melt temperature from \(T_h\) to \(T_2\). Assuming no heat exchange through the die and negligible compressibility of the melt (\(\Delta V = 0\)), the temperature rise through the die can be approximated as follows:

\[ \Delta V = 0 \]
\[ C_p = C_v \]
\[ \Delta H = \Delta E + \Delta (P \cdot V) = \Delta E + V \cdot \Delta P + P \cdot \Delta V = \Delta E + V \cdot \Delta P = 0 \]
\[ \Delta E = - V \cdot \Delta P = - V \cdot (P_2 - P_h) = V \cdot (P_h - P_2) = C_v \cdot \Delta T = C_p \cdot (T_2 - T_h) \]

\[ \Delta T = (T_2 - T_h) = \frac{V \cdot (P_h - P_2)}{C_p} \]

(2.9)

where
\[ \Delta E = \text{internal energy increase per unit polymer mass} \]
\[ V = \text{specific volume, i.e., volume of unit polymer mass} \]
\[ C_p = \text{specific heat measured at a constant pressure} \]
\[ C_v = \text{specific heat measured at a constant volume} \]

**Example 2.1 Estimation of Motor Size**

The target output rate of a high density polyethylene pipe extrusion line is 500 kg/h. The feed pellets are at room temperature and the desired melt temperature is 230 °C.

Calculate the minimum motor size of the extruder assuming 70% mechanical energy efficiency.

**Solution:**

The theoretical motor power at 100% mechanical energy efficiency in the adiabatic condition is calculated according to Eq. 2.6:

\[ G = 500 \text{ kg/h (1,101 lb/h)} \]
\[ \Delta H = (280 \text{ Btu/lb at 230 °C}) - (0 \text{ Btu/lb at RT}) = 280 \text{ Btu/lb} \]
\[ W_o^* = G \cdot \Delta H = 1,101 \text{ lb/h} \times 280 \text{ Btu/lb} = 308,280 \text{ Btu/h} \]
\[ = (308,280 \text{ Btu/h}) \div [2,544 \text{ Btu/(HP-h)}] = 121 \text{ HP} \]

The minimum motor power at 70% mechanical energy efficiency is calculated according to Eq. 2.8:

\[ W_o = (W_o^*) \cdot [100/(\% \text{ Mechanical energy efficiency})] = 121 \text{ HP} \times (100/70) = 173 \text{ HP} \]

**Example 2.2 Melt Temperature Rise Caused by Head Pressure**

Calculate the melt temperature increase caused by 68 atm (6.89 MPa or 1,000 psi) pressure drop through a die, assuming no heat loss through the die. Use the following approximate values for a common polymer:

\[ C_p = 2.72 \text{ J/g-C (0.65 cal/g-C)} \]
\[ V = 10^{-6} \text{ m}^3/\text{g (1 cc/g)} \]
Solution:
Equation 2.9 is used to calculate the melt temperature increase through the die caused by 68 atm (6.89 MPa or 1,000 psi) pressure drop. Noting 1 MPa = 10^6 N/m^2,
\[ V \cdot (P_h - P_2) = 10^{-6} \text{ m}^3/\text{g} \times (6.89 \times 10^6 - 0) \text{ N/m}^2 = 6.89 \text{ N-m/g or J/g} \]
\[ \Delta T = \frac{[V \cdot (P_h - P_2)]}{C_p} = 6.89 \text{ J/g} \div 2.72 \text{ J/g-C} = 2.5 \text{ °C (4.5 °F)} \]

2.8 Cooling

2.8.1 Barrel Cooling

All zones of an extruder are heated during the startup. At very low screw speeds, the heat generation inside the extruder is insufficient to maintain the set temperatures and all barrel zones call for additional heating. Modern extruders operating at high screw speeds usually generate excessive amounts of heat, and the barrel zones, except the first one or two zones next to the hopper, become overheated unless they are cooled. The first one or two zones, containing mostly the feed pellets at low pressure, do not generate much heat and may call for heating.

The melt film on the barrel surface is continuously scraped off the barrel by the advancing flight. Therefore, the heat transfer coefficient between the melt film and the barrel is high and barrel cooling is efficient [5]. Air cooling of the barrel is often insufficient, and water cooling is commonly used.

Heating of the barrel does not increase the melting capacity once the solid bed breaks up and the broken solid bed pieces are mixed in the melt. Heating is not necessary for about one-third of the barrel near the die, and barrel cooling is applied to lower the melt temperature in many operations. The viscosity of the melt on the barrel surface increases as the melt is cooled by barrel cooling, consuming higher motor power and generating more heat. Barrel cooling eventually becomes ineffective in lowering the melt temperature as the barrel temperature approaches the melting point of the polymer.

2.8.2 Screw Cooling

Screw cooling is inefficient because the melt on the screw surface is not scraped off the screw, and it is ineffective in lowering the melt temperature. However, screw cooling is necessary to avoid the feed bridging problem discussed in Section 2.3.1 or burning of the melt on the screw surface.

The feed bridging problem occurs for polymers with a low melting point caused by the feed pellets sticking and melting on the screw surface under the hopper. The screw surface under the hopper must be cooled to avoid the feed bridging problem. In this case, the screw is
bored only up to the first several turns of the flight in the feeding section and water is used as the cooling medium. The degree of cooling is regulated by the flow rate of water.

Polymer melts, being liquids, stick on metal surfaces. The melt inside an extruder sticks on the barrel surface and the screw surface. The melt does not burn on the barrel surface, because the melt on the barrel surface is continuously scraped off the barrel surface by the flight, and the barrel surface can be cooled to avoid overheating. However, the melt on the screw surface is not scraped off the screw surface and moves slowly with the longest residence time. The screw surface becomes hot because of the heat conducted from the melt, reaching the same temperature as the melt near the screw tip. Thermally unstable polymers burn on the screw surface, first at the screw tip. Even thermally stable polymers burn on the screw surface over a long period of weeks or months. The screw tip may be made with a long nose to reduce the gap between the screw tip and the adaptor, and also placed eccentrically to cause turbulence in the melt. If such maneuvers cannot stop the burning problem, the screw must be cooled. In this case, the screw is bored all the way to the screw tip. Water may be used as the cooling medium, but boiling of water and resultant hammering by the steam can be a problem. A temperature controlled heat-exchange oil with a boiling point higher than the melt temperature, such as silicone oil, is preferred.

2.9 Motor Power-Drive Torque Relationship, Screw Torque Strength, and Types of Motors

2.9.1 Motor Power-Drive Torque Relationship

Work is force times the distance that an object moves by the force.

\[ \text{Work} = \text{Force} \times \text{Distance} \]

Speed is the distance moved per unit time.

Power is the amount of work per unit time, or force \( \times \) speed.

\[ \text{Power} = \text{Work per unit time} = (\text{Force}) \times (\text{Distance moved per unit time}) = \text{Force} \times \text{Speed} \]

Referring to Fig. 2.16, the drive torque of an extruder is related to the motor power as follows:

\[ \text{Drive torque, } TQ_d = \text{Force} \times \text{Screw radius} = F \cdot R \]

\[ \text{Motor power} = \text{Force} \times \text{Speed} = F \cdot 2\pi R \left( \frac{\text{rpm}}{60} \right) = 2\pi (F \cdot R) \cdot \left( \frac{\text{rpm}}{60} \right) \]

\[ TQ_d = \left( \frac{60}{2\pi} \right) \cdot \left( \frac{\text{Motor power}}{\text{rpm}} \right) \]

(2.10)
2.9 Motor Power-Drive Torque Relationship, Screw Torque Strength, and Types of Motors

For motor power in kW (1 kW = 1,000 m-N/s) and drive torque in m-N, Eq. 2.10 becomes

\[
TQ_d = 9.554 \left( \frac{kW}{rpm} \right), \quad \text{m-N}
\]

(2.11a)

For motor power in HP (1 HP = 6,600 in-lbf/s) and drive torque in in-lbf, Eq. 2.10 becomes

\[
TQ_d = 63,025 \left( \frac{HP}{rpm} \right), \quad \text{in-lbf}
\]

(2.11b)

The drive torque is proportional to the motor power available per screw rpm, not the motor power itself. The drive torque with a given size motor decreases with increasing maximum screw rpm because the motor power available per screw rpm decreases. Unnecessarily high maximum screw rpm should be avoided.

Polymers with a high viscosity require a high drive torque with a low maximum screw rpm. Polymers with a low viscosity require a low drive torque with a high maximum screw rpm.

2.9.2 Screw Torque Strength

The feeding section of a screw has the deepest channel with the weakest mechanical strength. The screw at the start of the feeding section under the hopper is subjected to the maximum torque of the entire screw, and the screw breaks at this place if the torque exceeds the mechanical strength of the screw. The mechanical strength of a screw, in terms of the torque capability, ignoring the added strength of the flight, may be expressed simply by

\[
TQ_s = \frac{\pi \cdot (\text{Shear strength of metal}) \cdot [(R - H)^4 - r^4]}{2(R - H_r)}
\]

(2.12a)
where
\[ TQ_s = \text{screw torque strength} \]
\[ R = \text{screw radius} \]
\[ H_f = \text{feed channel depth} \]
\[ r = \text{cooling bore radius} \]

For screws without a cooling bore, Eq. 2.12a reduces to

\[ TQ_s = \frac{\pi \cdot (\text{Shear strength of metal}) \cdot (R - H_f)^3}{2} \quad (2.12b) \]

The shear strength of SAE-4140 steel, commonly used for manufacturing screws, is about 324 MPa (47,000 psi). Heat-treatment increases the shear strength by about 10%.

The screw torque strength must be sufficiently higher than the drive torque to avoid screw breakage. The feed channel depth is limited to avoid screw breakage for small screws of less than about 90 mm (3.543 in) D. Because the screw torque strength increases approximately by the third power of the screw diameter while the drive torque requirement increases by the \((2.5 - 2.8)^{th}\) power of the screw diameter, screw breakage is not a problem in design for large diameter screws. Breakage of large screws occurs occasionally in actual operations because of some defect in the steel or poor manufacturing of the screw.

A cooling bore along the axis of a screw not only reduces the screw torque strength, but also introduces machining marks where cracks can initiate. The screw should not be bored unless it must be cooled to avoid the feed bridging problem or the melt burning problem.

### 2.9.3 Types of Motors

The motor power of an extruder is expressed in terms of kW or HP. There are many types of motors and drives for extruders and downstream equipment [6] used in extrusion lines. Direct current (DC)-motors are widely used to attain variable screw speeds. For DC-motors, the speed is proportional to voltage and the motor power is equal to (voltage) \(\times\) (amperage). The amperage is referred to as the torque. Variable frequency alternating current (AC)-motors also provide variable screw speeds. Flux vector-controlled, variable frequency AC-motors represent the latest drive technology with the best torque and speed control [7].

The drive torque delivered to the screw by the motor through the drive chain (transmission and gear box) is proportional to motor power divided by speed, as described in Section 2.9.1. There are two types of motors with different characteristics as shown in Fig. 2.17:

- Constant torque type
- Constant torque – constant power type
Figure 2.17 Two types of motor characteristics: (a) Constant torque type; (b) Constant torque-constant power type

For the constant torque type, the motor power increases proportional to speed attaining the maximum power at the maximum speed. Thus the torque is constant over the entire speed range.

For the constant torque – constant power type, the motor power increases proportional to speed, attaining the maximum power at the base speed and then remains constant between the base speed and the maximum speed. The torque is constant up to the base speed but decreases beyond the base speed. This motor type is appropriate if an extruder is used for both a high viscosity polymer requiring a high drive torque at low screw speeds, and a low viscosity polymer requiring a low drive torque at high screw speeds.

2.10 Wear

The screw of an extruder is not mechanically held in a fixed position and it can move freely, rubbing on the barrel. The screw and the barrel undergo wear with usage. Wear occurs mostly along the compression section of the screw, where the feed polymer is not completely molten and a high pressure is generated. Both the screw and the barrel wear concentrically and uniformly in most cases. If the weight of the screw on the bottom of the barrel causes the wear, the screw will wear concentrically but the barrel will wear only at the bottom.

Wear may be caused by abrasion, chemical corrosion, imperfect alignment of the barrel, non-straight screw, poor welding of the hard metal layer on the flight land, or high pressure fluctuation inside the screw.

Because the barrel expands and may distort significantly upon heating, it should be aligned after heating. The barrel is more difficult, time consuming, and expensive to change than the screw. The internal barrel surface is made harder than the screw, making the screw wear rather than the barrel. The barrel should last for tens of years in
normal usage. Most barrels have a bi-metallic construction with a very thin, hard internal layer of a special metal alloy centrifugally cast on a common steel. A corrosion resistant metal alloy is used for the internal layer if necessary. The special metal alloys used for the internal layer are very hard but brittle. The internal surface of some barrels are made hard by chemical treatment, but the hardness is much less than those of bi-metallic barrels.

Screws are made of a common steel, selected for its hardness and machining characteristics. A screw rubs on a barrel only on its flight land. The flight land is made hard by welding a special hard metal alloy (or ceramic), chemical treatment, or heat treatment. The performance of a screw deteriorates as the flight land wears with time. When the wear becomes excessive, the screw should be replaced or repaired. The performance record with time from the startup of the screw is necessary to determine the extent of the wear.

Normal, slow abrasive wear of the flight land of a screw is caused by the fluctuating pressure differential around the screw. The pressure inside the screw fluctuates with time and also it is not uniform around the screw at a given moment, resulting in a higher pressure on one side of the screw than the other side. The pressure differential occurs randomly around the screw, and the screw is rubbed on the entire surface of the barrel by the random pressure differential. The rate of normal abrasive wear for metals increases proportional to the rubbing velocity and approximately to the $3^{rd}$ power of the rubbing pressure [8]. Abrasive polymer feeds, fillers, or additives accelerate the wear. Abrasive ingredients cause wear on all screw surfaces, including the flight and the screw root.

Excessive abrasive wear may be caused by imperfect alignment of the barrel or poorly manufactured screw. The screw may not be perfectly straight or the abrasion resistant layer on the flight land may be poorly welded. Delamination of the welded layer from the flight land may occur in the worst case.

Corrosive wear is caused by a corrosive ingredient in the feed or a corrosive chemical generated during extrusion. The screw is plated with a corrosion resistant metal such as chrome or nickel to resist corrosion. The screw itself is made of a corrosion resistant metal, for more rigorous requirements.

### 2.11 Extruder Size and Instrumentation

#### 2.11.1 Extruder Size

The size of an extruder is given by diameter $D$ and length $L$. The length is usually given in terms of $L/D$ ratio. The standard commercial extruders in the United States have $D = 1.5, 2.5, 3.5, 4.5, 6, 8, 10, 12,$ or $14$ in and $L/D = 24, 30,$ or $36$. Melt extruders can be as
large as 24 in D. The diameters of the standard commercial extruders elsewhere in the world are sized in metric units (mm).

The maximum output rate of a plasticating single-screw extruder with solid polymer feeds is roughly proportional to the barrel surface area. Longer extruder with higher L/D ratio, instead of larger diameter, is a cost effective way of increasing the barrel surface area for higher output rate and the trend for higher L/D ratio will continue.

### 2.11.2 Instrumentation

A modern extruder comes well equipped with various instruments for controlling the operating variables and monitoring the performance. Instruments for monitoring the following operating variables and performance of an extruder are essential.

- Screw rpm
- Barrel zone temperatures
- Motor power or amperage
- Melt temperature
- Die pressure
- Head pressure $P_h$

The performance of an extruder results from the complex interactions between the solid conveying, melting, and metering functions of the screw. Continuous monitoring of the operating variables and the extruder performance helps to understand the screw functions and the problems correctly, leading to optimization of the screw design and the operating conditions.

Two additional pressure measurements along the barrel, one called “$P_1$” at about one-third, and the other called “$P_2$” at about two-thirds of the barrel length from the hopper, are desired to understand what is happening inside the screw. The three pressure data, $P_1$, $P_2$ and $P_h$, provide diagnostic information. An unreasonably low or high value of $P_1$ indicates insufficient or excessive solid conveying rate, respectively. A low value of $P_2$ indicates insufficient supply of melt to the metering section in comparison to the pumping capability of the metering section. Severe fluctuations in $P_1$ or $P_2$ indicate inconsistent feeding, feed bridging, or wedging of the solid bed in the compression section. If the geometric compression or tapering of the screw channel in the compression section is more than the melting rate, the solid bed cannot go through the screw channel and becomes wedged temporarily until it melts enough to accommodate the geometric compression of the screw channel. If $P_1$ and $P_2$ are stable, the head pressure also should be stable.

The head pressure, measured at the end of the screw before the screen pack, slowly increases with time as the screen pack becomes clogged, slowly decreasing the output rate. The die pressure, measured at the adaptor after the screen pack, decreases as the
output rate decreases. The die pressure should stay constant at a constant output rate and a constant melt temperature. A widely used feedback control slowly increases the screw rpm to maintain a constant die pressure, as the screen pack becomes clogged, assuring a constant output rate.

### 2.12 Rubbing Mechanisms of Solid Polymer on Metal Surface

It is well known that feed pellets are compacted into a tightly packed solid bed inside a single-screw extruder. The solid bed rotates with the screw virtually at the same velocity as the screw, rubbing and melting on the barrel surface under high pressures. The solid bed slips slightly on the screw surface as it rotates with the screw, and the slippage of the solid bed on the screw results in the output rate. The extrusion behavior of a polymer depends on the rubbing mechanisms of the solid polymer on the metal surfaces of the barrel and the screw.

Figure 2.18 shows four possible rubbing mechanisms of a solid polymer on a metal surface. At low metal temperatures below the melting (or glass transition) range of the polymer, the rubbing mechanism is “friction”. Friction may occur with or without grinding the polymer. Grinding occurs if the polymer is brittle and the shear stress $\tau$ developed between the polymer and the metal surface is high, exceeding the shear strength of the polymer. Grinding produces fine polymer powders on the metal surface, and it corresponds to a high wear mechanism. $\tau$ in friction mainly depends on pressure $P$. $\tau$ is proportional to $P$ in the ideal frictional mechanism, but $\tau$ increases less than proportional to $P$ for polymers.
At high metal temperatures well above the melting range of the polymer, the rubbing mechanism is “melting” and a thin melt film is formed between the polymer and the metal surface. The melting mechanism forming a smooth melt film on the metal surface is denoted by M-1 in Fig. 2.18d. The melting mechanism forming lumps of the melt on the metal surface is denoted by M-2 in Fig. 2.18d. The M-2 mechanism may result from poor adhesion of melt on metal surface, high melt elasticity, or melt instability at the high shear rates in the thin melt film. The shear stress $\tau$ in the melting mechanism mainly depends on rubbing velocity ($U$), increasing exponentially with increasing $U$, similar to the dependence of melt viscosity on shear rate. Rigid, highly crystalline polymers, such as polyesters, nylons, polypropylene, and high density polyethylene, and rigid amorphous polymers (glassy polymers), such as polystyrene and polycarbonate, make a distinct transition from the frictional mechanism to the melting mechanism with increasing metal temperature.

Soft, semi-crystalline polymers with a broad melting range, such as low density polyethylene, exhibit intermediate rubbing mechanisms between friction and melting. “Tearing” and “unstable melting” are two representative intermediate rubbing
mechanisms. Tearing occurs when the polymer at the metal temperature behaves like an elastomer, and it produces rubber-like, abraded polymer pieces on the metal surface. Unstable melting combines the tearing and melting mechanisms, producing melt streaks on the metal surface. High shear stresses are developed in tearing and unstable melting. The rubbing mechanism of a solid polymer on a metal surface depends on the thermodynamic, mechanical, and melt rheological properties of the polymer over the temperature range from the polymer temperature to the metal temperature. These properties, in turn, depend on the molecular and morphological characteristics of the polymer.

All barrel zones of an extruder, except the first zone next to the hopper, are set at temperatures far above the melting point of the polymer in most cases, and the rubbing mechanism on the extruder barrel will be melting. The first zone is set at a lower temperature, but still well above the melting point of the polymer, to avoid the sticking problem of the feed materials on the feed throat and the screw. A barrel temperature below the start of melting mechanism, where grinding, tearing or unstable melting mechanism occurs, should be avoided because a unnecessary high torque would be required without effectively melting the polymer.

### 2.13 Relationships Between Screw Channel Geometries

Referring to Chapter 1; Fig. 1.3, the pitch $P$ and the helix angle $\phi$ of a flight are related. Figure 2.19 shows one turn of the flight removed from the screw root and unwrapped on a flat surface. The following relationship is found:

$$\tan \phi = \frac{P}{\pi D}$$

$$\phi = \tan^{-1} \left( \frac{P}{\pi D} \right)$$

For the square-pitch with $P = D$, $\phi = 17.65^\circ$ is found using Eq. 2.13.

The cross-sectional area of the screw channel used for flow rate calculations is equal to $(\text{the channel depth } H) \times (\text{the channel width } W \text{ measured perpendicular to the flights})$. The relationship given below between the pitch $P$ and the channel width $W$ of a single-flighted screw is also shown in Fig. 2.19.
2.14 Variables Controlling Polymer Extrusion

Th e performance of an extruder for a polymer depends on polymer properties, feed characteristics, screw design parameters, and operating conditions, as discussed previously. Also, feeding conditions assuring a consistent feeding rate are essential. Table 2.1 summarizes these variables. Descriptions of the polymer properties relevant to processing are presented in Chapter 3.

Table 2.1 Variables Controlling Polymer Extrusion

<table>
<thead>
<tr>
<th>Polymer properties</th>
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</thead>
<tbody>
<tr>
<td>Thermodynamic properties</td>
</tr>
<tr>
<td>Melting characteristics – melting range</td>
</tr>
<tr>
<td>Heat capacities and thermal conductivities of solid and melt, heat of fusion</td>
</tr>
<tr>
<td>Melt rheological properties</td>
</tr>
<tr>
<td>Viscosity; elasticity; shear sensitivity; temperature sensitivity</td>
</tr>
<tr>
<td>Mechanical properties</td>
</tr>
<tr>
<td>Modulus; yield strength</td>
</tr>
<tr>
<td>Solid density and melt density</td>
</tr>
</tbody>
</table>
### 2 Physical Description of Single-Screw Extrusion

<table>
<thead>
<tr>
<th>External friction on metal surface</th>
<th>Thermomechanical stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additives</td>
<td></td>
</tr>
</tbody>
</table>

**Feed characteristics**
- Size and shape of feed pellets, and their distribution
- Bulk density of feed pellets
- Internal friction of feed pellets

**Feeding conditions**
- Feed temperature – preheating or drying of the feed
- Gravity, forced or metered (starved) feeding
- Constant feeding rate, in weight
- Consistent composition if more than one component feed

**Recycling**

**Screw design parameters**
- Pitch (or lead)
- Number of parallel flights
- Feeding section depth and length
- Compression (or transition) section length
- Taper or reduction rate of the channel area in compression section
- Metering section depth and length
- Compression ratio (CR)

**Mixing section design**
- Special channel geometry
- Single or multiple stages

**Operating conditions**
- Screw rpm
- Barrel temperature settings
- Head pressure
  - Die design; screen pack; breaker plate; adaptor
- Screw temperature control

**References**

**General Readings**
Extrusion Solutions, collection of consultants’ answers to questions, updated annually by the Extrusion Division of SPE
Rauwendaal, C., Polymer Extrusion, Hanser, Munich (2001)