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Equipment Overview

1.1 Process Issues

Efficient melting of polymer pellets or powder is an essential process requirement to obtain a quality product from either single- or twin-screw extruders. An example of an issue associated with poor melting is product surface defects. Tiny unmelted polymer particles, gels, undispersed solid fillers, or additives often contaminate film products when poorly designed screws are used in production [1]. These contamination particles can be caused by the incomplete melting of the resin, especially in bimodal polyolefins [2], or by not having appropriate dispersive mixing elements in the device [3]. A major source of gels in single-screw extruders is screw channels with small radii at the base of the flights; the cause and solution of this issue will be discussed in a later chapter. Another source of gels is contamination during shipping from poorly cleaned railcars to cardboard and trash found in Gaylord boxes. Although not usually a problem when using a twin-screw extruder to melt low-viscosity polymer powders, in single-screw extruders this type of powder can cause a change in the melting mechanism, resulting in unmelted polymer in the extrudate. This issue will be discussed in a later chapter. For either type of extruder, a source of gels in the extruded product is improperly designed extruder-to-die transitions and/or transfer lines where the wall stress is not greater than 20 kPa as the polymer flows [4]. In the twin-screw extruder, an unstable melting process that results in surging can occur. The melt quality can be OK, but obviously not good for any downstream handling for precise profiles, even if a gear pump (GP) is in place. Also, in the single-screw extruder, an improperly designed barrier flighted single screw will melt the polymer but often cause surging at the die due to resin bridging at an improperly designed inlet transition.

■ 1.2 Homogeneous Melt and Composition

For most polymer extrusion processes, the key to economic success is to have an extruder that delivers a polymer melt which is homogeneous, with respect to both composition and temperature, to the forming device, usually a film, strand, or profile die. When developing multiphase polymer melts that often contain suspended solids, the twin-screw extruder is almost always the processing equipment of choice. To accomplish this task, the extruder—which is generally fed with polymer powders or pellets produced by the chemical manufacturer—conveys, “melts”, and mixes the fluid polymer with any other additional required material, such as solid filler, and delivers the mixed homogenized melt to the forming device. For example, Campbell et al. recently investigated the mixing process of fillers ranging from nano- to micron-sized particles. This work has shown mixing in a co-rotating twin screw to be substantially influenced by the polymer rheology [5–7]. In the case of incorporation of solid fillers, up to a 60 volume fraction in the melt, Wetzel et al. found that when the loading exceeds a percolation concentration of about 15% by volume, the structure developed by the filler has a strong influence on the mixing efficiency [8–10]. Therefore, the introduction of fillers, both comingled with the polymer powder or pellets and downstream into the polymer melt via the twin-screw extruder, is an important functional unit operation in the polymer industry. However, in this book the focus will be on developing and delivering homogeneous polymer melts—either from unfilled homopolymers or from previously compounded multicomponent polymer materials, such as particulate, fiber-filled thermoplastics or color concentrates—to the die. The objective of the following chapters will be to provide a detailed compare-and-contrast perspective of the different mechanisms inherent in single-screw and co-rotating twin-screw extruders as they accomplish this task.

■ 1.3 Extruder Mechanical Design Comparison

Before going into detail regarding conveying, melting, and mixing mechanisms associated with the two extruder configurations, it is useful to compare and contrast from a macroscopic perspective many of the design features of these two devices; single-screw extruder: Figure 1.1 [11], co-rotating twin-screw extruder [12]: Figure 1.2.

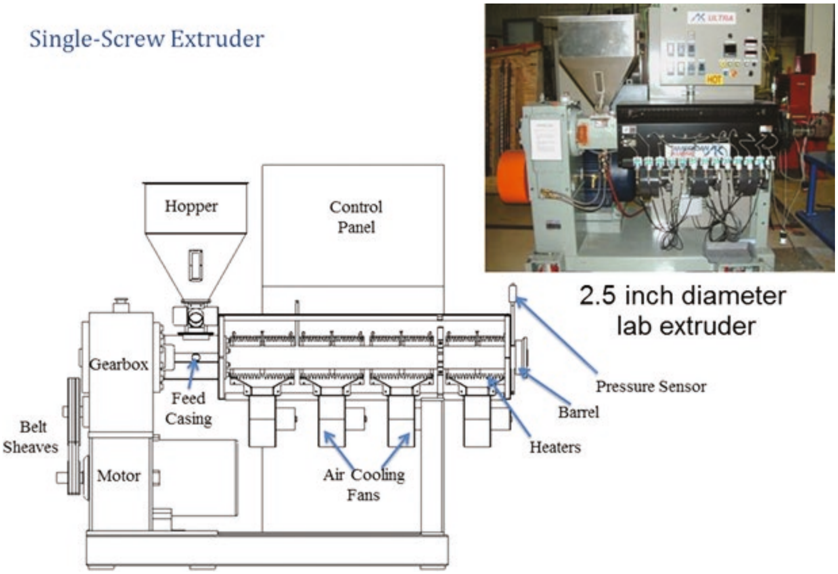

Figure 1.1 Typical single-screw extruder (courtesy of G. A. Campbell and M. A. Spalding, *Analyzing and Troubleshooting Single-Screw Extruders,* 2nd ed., Hanser (2021))

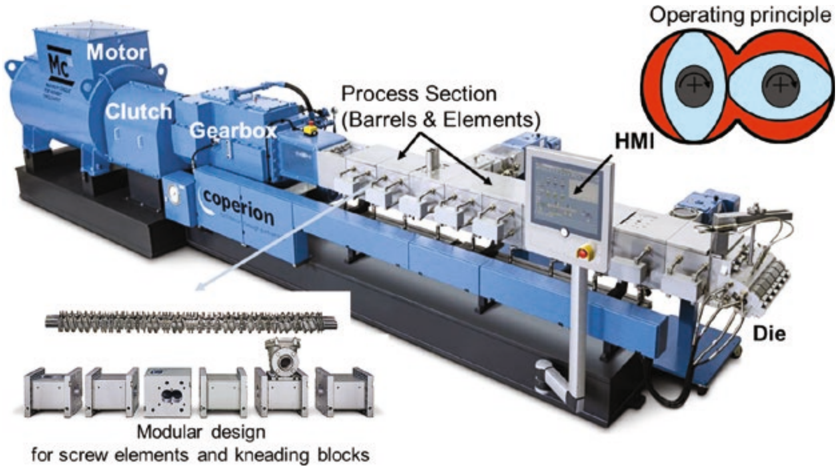

Figure 1.2 Basic layout and main components of the twin-screw extruder with drive power available from 10 kW to 12 MW and rates from 1 kg/h to 100 t/h (courtesy of Coperion Corporation)

Each extruder system consists of a motor, coupling mechanism, gearbox, process section, and shaping device, such as a strand, film, or profile die.

The single-screw extruder has a process section usually constructed from a single piece barrel and a solid screw; see Figure 1.3. The co-rotating twin-screw process section, as illustrated in the bottom left-hand corner of Figure 1.2, is built up from modular components (both barrels and screw elements). The operating principle of the twin screw, as illustrated in the top right-hand corner of Figure 1.2, is based on two parallel screw shafts where the crest of one screw element wipes the root of the other [13, 14].

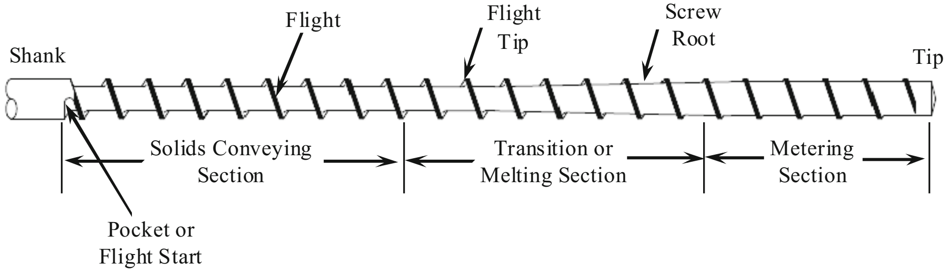

Figure 1.3 Schematic of a typical single-flighted screw (courtesy of G. A. Campbell and M. A. Spalding, *Analyzing and Troubleshooting Single-Screw Extruders,* 2nd ed., Hanser (2021))

Both the single screw and the twin screw have similar degrees of freedom with respect to geometry, power transmission, and screw speed [15]; however, the self-wiping criterion places constraints on the overall twin-screw extruder design flexibility. While the single-screw extruder can have multiple different channel depths along the axial length of the screw profile to meet process requirements (Figure 1.3), the cross-sectional geometry of the twin-screw extruder is fixed at a constant channel depth to maintain self-wiping. The twin-screw cross-sectional geometry is defined by three dimensions: screw diameter (either the outer diameter (D_o) or the inner (root) diameter (D_i)), D_o/D_i ratio, and centerline distance (a) between the two screw shafts (Figure 1.4). Once two of the above three criteria are defined, the other one is fixed. For a constant centerline distance, as the D_o/D_i ratio is increased, the extruder D_o increases and the D_i decreases. Therefore, the diameter ratio can be used as a comparative measure of the free cross-sectional area among twin-screw extruders, and thus of the internal free volume per unit length as well. The larger the D_o/D_i ratio, the greater the internal free volume per unit length of the extruder. Therefore, D_o/D_i is a relative measure of the maximum theoretical volumetric throughput capacity of the extruder. However, as is discussed in the next paragraph, D_o/D_i cannot be increased without at some point impacting the power transmission capacity of the screw shaft [14].

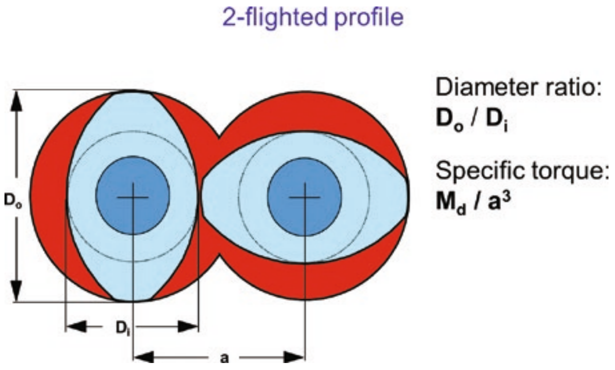

Figure 1.4
Characteristic dimensions of co-rotating twin screws (courtesy of Coperion Corporation)

D_o/D_i has several additional influences on the extruder design and operating conditions. In addition to being a comparative measure of internal free volume, D_o/D_i defines the average shear rate constant for the extruder geometry. The average shear rate constant is determined by integrating the shear rate as a function of the channel depth over the entire screw profile. The average shear rate of a fully filled channel can then be determined by multiplying this constant by the screw rpm. This average shear rate can be used to compare extruders with different diameter ratios as well as extruders run at different rpm values. For example, as D_o/D_i is increased, the channel depth of the extruder increases and the shear rate constant decreases. Finally, as D_o/D_i increases, the shaft diameter available for power transmission is reduced; see Figure 1.5. This creates a conflicting scenario. An extruder with a small D_o/D_i has reduced free volume, but significant power transmission design capacity. On the other hand, a larger-D_o/D_i extruder has a greater volumetric throughput capacity, but geometric constraints limit the shaft diameter and therefore the power transmission capacity. Consequently, an appropriate balance between required power transmission capability and available free volume must be determined so that neither one is a process-limiting parameter. The ideal situation exists when a process is simultaneously power-limited, and volume-limited.

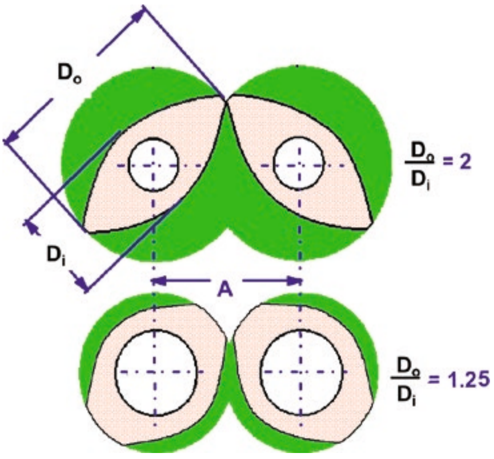

Figure 1.5
Relationship between D_o/D_i ratio and free volume (courtesy of Coperion Corporation)

As an example of the power/volume trade-offs discussed above, Table 1.1 shows the difference in free cross-sectional area, average shear rate, and power/volume ratio expressed as torque capacity/centerline distance cubed (M/a^3) of two currently available co-rotating twin-screw extruders with the same centerline distance but D_o/D_i ratios of 1.55 and 1.80, respectively. As expected, the power/volume ratio of the extruder with the 1.80 D_o/D_i ratio is lower than that of the 1.55 D_o/D_i extruder, due to shaft limitations.

Table 1.1 Impact of D_o/D_i on Free Cross-Sectional Area and Average Shear Rate

Machine Size	D_o/D_i	Free Cross-Sectional Area [cm^2]	Average Shear Rate (300 rpm) [s^{-1}]	Torque/Centerline^3 (M/a^3) [$N \cdot m/cm^3$]
ZSK-92	1.55	46.0	100	18.0
ZSK-98	1.80	62.9	60	11.3

While both extruders could be used for similar processing tasks, the processing length, screw configuration, and operating conditions would need to be different. However, when power versus volume is considered, the 1.55 D_o/D_i extruder would be capable of the highest rates for energy-intensive processes such as processing glass-filled nylon, but the 1.80 D_o/D_i extruder would win out for processing low bulk density material not requiring a significant energy input, such as 60% talc-filled PP.

1.4 Extruder Screw Design/Unit Operations Comparison

The single-screw extruder is generally divided into three primary sections/unit operations (Figure 1.3): section 1, solids conveying; section 2, melting/mixing; and section 3, metering. Additional unit operations, such as enhanced melt-mixing and discharge pressurization elements, are often incorporated into the metering section. Much of the mixing, such as dispersion of color concentrates, is accomplished in the melting section of the single screw.

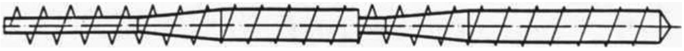

Figure 1.6 Two-stage single-screw profile

Additionally, the three screw sections have separate heater zones on the barrel to provide energy to the screw where required, as seen in Figure 1.1, and to remove energy (providing cooling) when the polymer's viscosity leads to unacceptable high melt temperatures. There are, however, two-stage single-screw designs (Figure 1.6) that have an increased channel depth following the first metering section to allow additional material to be introduced, but this design is usually used to volatilize and remove low molecular weight contaminants such as moisture. The process section for a co-rotating twin-screw compounding line can require the same three primary unit operations, solids conveying, melting/mixing, and metering/conveying, when used for processes that require no compounding of multiple components or other complex processing functions. Such an application is melting nylon pellets for a monofilament spin line. However, more typically, the compounding process can be broken down into unit operations as depicted in Figure 1.7. These are: introduction of the feed material, solids conveying, melting (softening, phase transformation), additive incorporation, mixing (dispersive, distributive), atmospheric venting, mixing, degassing/devolatilization, discharge pressurization, and discharge shaping [16].

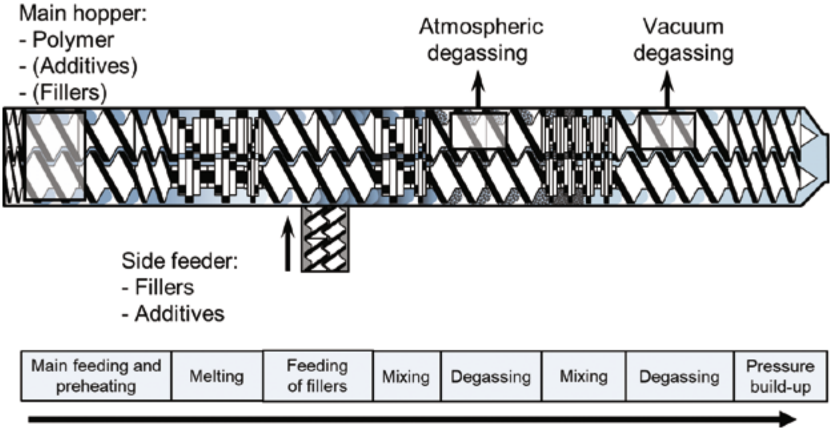

Figure 1.7 Typical co-rotating twin-screw compounding line unit operations (courtesy of Coperion Corporation)

Most single-screw extruders have one of two typical screw designs: single-flighted, Figure 1.3, or barrier screws, Figure 1.8. The barrier flight is undercut from the main flight to allow molten resin to transfer from the solids-conveying channel to the melt channel. The entrance transition to the solids channel of the barrier screw must be carefully designed or the pellets will bridge when they leave the screw feed section.

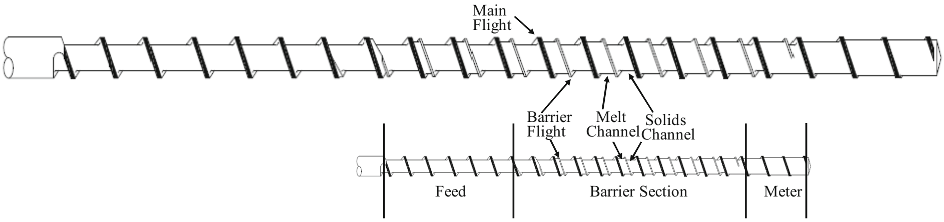

Figure 1.8 Schematic for a barrier melting section (courtesy of G. A. Campbell and M. A. Spalding, *Analyzing and Troubleshooting Single-Screw Extruders,* 2nd ed., Hanser (2021))

As illustrated in Figure 1.3, the single flight consists of a single helix along the length of the shaft. This first section of the screw, the feed zone, is normally flood fed from the hopper and has a deep channel depth to effectively take in and convey the lower bulk density solid feed. The next section, the melting zone, has a decreasing channel depth along the down-channel axial direction to compact and subsequently melt the feedstock. The final section, the metering zone, conveys the melted polymer and generates the required pressure to force the polymer melt through the shaping device attached to the end of the extruder barrel. The pitch, or lead, of this screw is normally constant along the entire length of the screw; however, the pitch may be changed in differing sections of the screw to control the solids feed rate in the feed section or to increase the pressure development in the metering section. The pitch, or lead, is determined by the distance between two consecutive flights along the axial direction of the screw of the same helix and if the pitch/lead is equal to the barrel diameter, the screw is referred to as a square-pitched screw. The screw can have more than one flight (helix or start). Multiple flights are most common in large-diameter screws in the metering sections to enhance pressure development to overcome the back pressure from the die.

For the twin screw, elements are often constructed with a single, double, or triple helix; see Figure 1.9. So far, no commercial twin screw has incorporated more than the triple helix design. Figure 1.10 illustrates a two-flighted (helix) geometry. As shown, the pitch is the distance between the first and the third crest. The proper definition is that pitch is equal to the axial distance traveled when tracing the crest over 360 degrees.

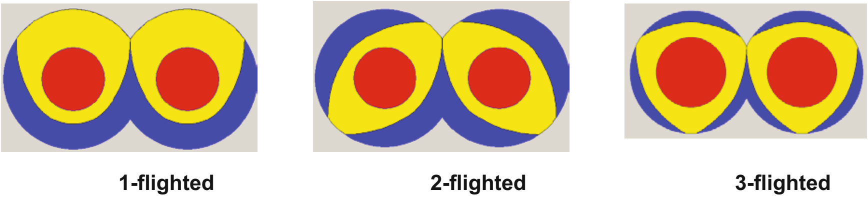

Figure 1.9 Examples of twin-screw single-, double-, and triple-flighted cross-section geometry (courtesy of Coperion Corporation)

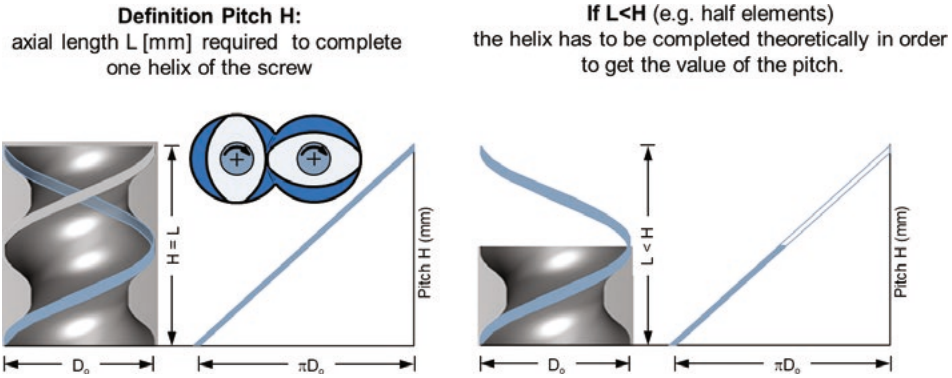

Figure 1.10 Pitch defined for the two-flighted twin-screw profile (courtesy of Coperion Corporation)

For many polymers, this barrier screw design (Figure 1.8) has a higher melting rate than the basic screw design because the solid bed is kept closer to the moving surfaces of the screw, thus producing more dissipative energy to enhance melting. As discussed in detail in Campbell and Spalding [11], in the solids-conveying section, plastic materials, usually in the form of pellets or powders, are flood fed continuously through a hopper into the extruder. Then, the polymer moves down-channel, pushed by the rotating flights of the screw. Because of heat conduction through the barrel wall and mechanical friction, the solid polymers are heated and softened first at the polymer barrel interface after the solid bed is compacted. As soon as the temperature of the solid polymer reaches its melting point (for crystalline polymers) or softening point (for amorphous polymers), a viscous polymer melt is formed in the so-called delay zone, that is, before the section of the screw where the core/root is increasing in diameter. The detailed theory of how the melt encapsulates the solid bed will be presented in a later chapter. Most of the bed heating is viscous dissipation caused by the shearing action in the film due to the relative motion of the screw surfaces and the solid bed motion relative to the stationary barrel. This energy is then conducted into the solids, melting crystalline resins and softening amorphous resins to the point that they will flow in the shear field next to the barrel. In the melt-conveying (metering) section, polymer melt is “pressurized” and readied to be pumped through the die. For a single-screw extruder with a properly designed screw geometry, the metering section is the rate-controlling part of the screw and the transition and feed sections must be properly designed to complement the dynamics in the metering section.

Co-rotating twin-screw extruder screw configurations, as pointed out previously, are constructed from modular component elements assembled in a specific sequence to implement the unit operations required to accomplish the process task. Figure 1.11 illustrates a barrel and screw configuration sequence for homopolymer powder to pellet conversion. In general, there are two types of elements: conveying elements, whose primary function is to transport material in the down-channel direction, and kneading blocks, whose function is to impose a "stress" on the material to perform some energy-intensive task such as melting, dispersion, or homogenization. Figure 1.12 displays several types of conveying elements (top row) and kneading blocks (bottom row).

Figure 1.11 Barrel and screw configuration sequence for homopolymer powder to pellet conversion (courtesy of Coperion Corporation)

Figure 1.12 Basic elements of the twin-screw compounder; top row: conveying elements, bottom row: kneading blocks (courtesy of Coperion Corporation)

Twin-screw conveying elements are inherently different from the conveying geometry of the single screw. Single-screw extruders screws typically have a constant pitch, but a depth that varies from the feed intake zone (deep) to the metering discharge zone (shallow); see Figure 1.3. On the other hand, twin-screw extruder conveying elements maintain a constant channel depth, but vary the pitch. Standard screw bushings are constructed with pitches ranging from approximately 0.5 *D* to 2.0 *D*, where *D* is the machine diameter; see Figure 1.13. Large-pitch elements (1.5 *D* to 2.0 *D*) might typically be used in feed or devolatilization areas of the extruder. Medium-pitch elements (approximately 1.0 *D*) are used to transport material between unit operations (i. e., feeding, mixing, and vacuum devolatilization). Narrow-pitch elements (0.5 *D* to 0.7 *D*) are used in areas where compaction of material and 100% fill is desired, such as to build melt pressure before kneading blocks or the die. Up to approximately 2.5 *D*, a greater element pitch results in increased down-channel material conveying. This results in a decrease in residence time, degree of fill, as well as a narrower residence time distribution. However, while there is an increased drag flow capacity associated with a greater pitch, there is also an increased sensitivity to pressure flow. That is, as the pitch of an element is increased, the drag flow conveys material in the down-channel direction at a faster rate. However, if there is a restrictive force placed in the flow path, the greater-pitch element is less effective in building up the pressure necessary to push material past the restriction [17]. See Section 6.5.3 for a more detailed discussion. Reverse pitch elements are used to generate back pressure and therefore create sections of 100% fill which, for example, can be used to separate unit operations or totally fill a mixing section.

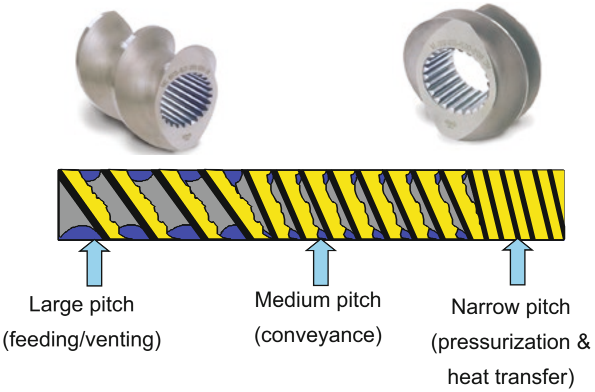

Figure 1.13 Typical utilization for large (~1.5–2.0 × screw diameter), medium (~1.0 × screw diameter), and narrow (~2/3 × screw diameter) pitch conveying elements (courtesy of Coperion Corporation)

The basic building blocks for mixing in the co-rotating, intermeshing-type twin-screw extruder are kneading blocks and special mixing bushings. Special bushings include slotted elements, toothed mixing elements and blister rings, or the self-wiping equivalent element [18–22]. Standard conveying-type screw bushings are also used in certain circumstances.

Just as screw bushings are characterized by pitch (i. e., flight angle), kneading blocks can be characterized by individual disc length (width), Figure 1.14, and stagger angle between successive discs, Figure 1.15. Kneading blocks introduce both a distributive and a dispersive mixing component into the system. The rela-

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