Basic Process

The extruder is one of the most important machinery in the polymer processing industry. To extrude means to push or to force out. Extrusion is a polymer conversion operation in which a solid thermoplastic material is melted, forced through an orifice (die) of the desired cross section, and cooled. The extruded product is referred to as the extrudate. The process is used for compounding plastics and for the production of tubes, pipes, sheet, film, wire coating, and profiles. Although there are many types of extruders, the most common types are single-screw extruders, intermeshing twin-screw extruders, and ram extruders for special processes.

Construction of single-screw extruders

A single-screw extruder (Fig. 2.1) consists of a screw in a metal cylinder or barrel. One end of the barrel is attached to the feed throat while the other end is open. A hopper is located above the feed throat and the barrel is surrounded by heating and cooling elements. The screw itself is coupled through a thrust bearing and gear box, or reducer, to a drive motor that rotates the screw in the barrel. A die is connected to the "open" end of the extruder with a breaker plate and screen pack (or a screen changer) forming a seal between the extruder and die. During extrusion, resin particles are fed from the hopper, through the feed throat of the extruder, and into the extruder barrel. The resin falls onto the rotating screw and is packed in the first section or feed zone of the screw. The packed particles are melted as they travel through the middle section (transition or compression zone) of the screw, and the melt is mixed in the final section or metering zone. Pressure generated in the extruder forces the molten polymer through the die.

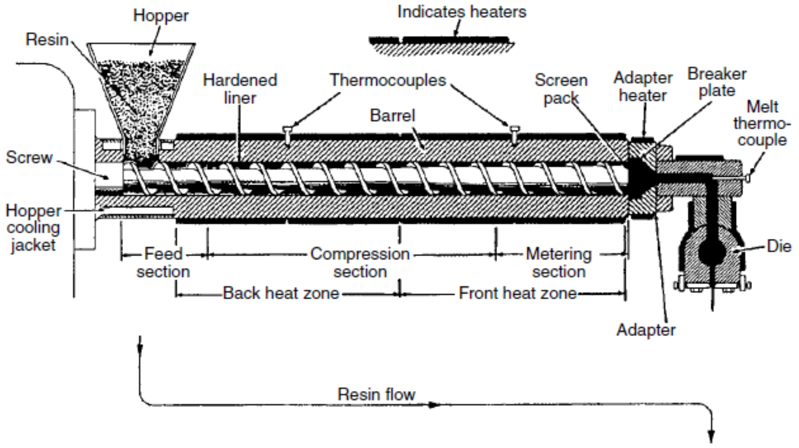


Fig 2.1. Single-screw extruder

Extruder drive motors must turn the screw, minimize the variation in screw speed, permit variable speed control (typically 50 to 150 r/min), and maintain constant torque.

Feed Throat

The feed throat fits around the first few flights of the screw and is usually separate from the barrel of the extruder. It is insulated from the barrel and cooled with water to prevent bridging and premature melting of the resin particles. The feed port is the opening in the feed throat. Standard feed ports (Fig. 2.2*a*) are round or square and should match the geometry and size of the hopper opening. Although these ports are suitable for plastics pellets and some granules, specialized designs are employed with other materials. An undercut feed port (Fig. 2.2b), which exposes the bottom of the screw, is used for rolls and strips of film or fiber, for film scrap, and for polymer melts. A sloped feed port (Fig. 2.2 c) is better suited to irregularly shaped particles, whereas a tangential feed port (Fig. 2.2 *d*) can be used for powders and regrind.

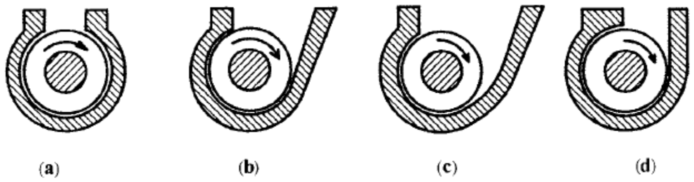


Fig 2.2 Feed port designs: (a) standard feed port, (b) undercut feed port , (c) sloped feed port, (d) tangential feed port

The feed hopper feeds material to the extruder. Single-screw extruders are usually fed gravimetrically through standard conical or rectangular hoppers (Fig. 2.3a). Although pellets and some granules flow smoothly in these hoppers, powders and other particles often require modifications for proper feeding. A spiral hopper (Fig. 2.3*b*) improves dry flow, while vibrating pads or hammers are sometimes attached to hoppers to break up bridges (blockages at the base of the hopper). Vacuum feed hoppers reduce the trapped air that hinders proper feeding. In crammer feeders (Fig. 2.3c), an auger forces material into a barrel, whereas metered (starve) feeding (Fig. 2.3*d*) uses an auger to feed a set amount of material to the barrel. Starve feeding not only minimizes bridging and air entrapment but also prevents vent flooding in vented barrel extruders.

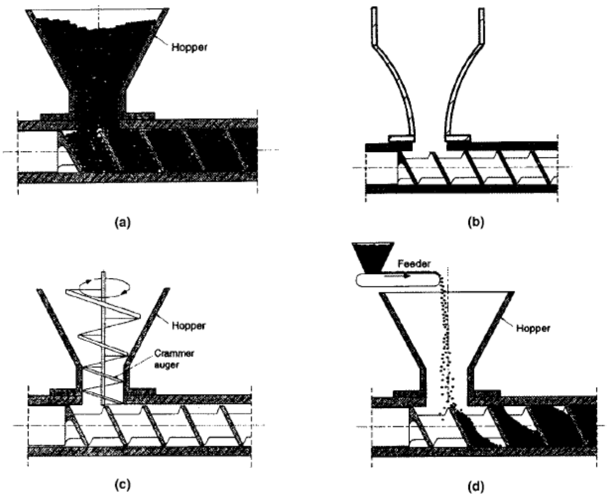


Fig 2.3. Hopper designs: (*a*) standard hopper with gravimetric feed,33 (*b*) spiral hopper, (*c*) crammer feeder and (*d*) standard hopper with metered feed.

The barrel is a metal cylinder that surrounds the screw. One end fastens to the feed throat and the opposite end connects directly to the die adapter. Since extruder barrels must withstand pressures up to 70 MPa, they are usually made from standard tool steels, with special tool steels required for corrosive polymers. Extruder barrels typically have length-to-diameter (*L/D*) ratios of 24:1 to 36:1, but they can be larger. Since melting occurs over a longer transition zone, longer barrels provide increased output. The clearance between the barrel and screw flights is typically 0.08 to 0.13 mm. To reduce barrel wear, barrels are nitrided or bimetallic liners are inserted into the barrel.

The breaker plate acts as a seal between the extruder barrel and the die adapter, thus preventing leakage of the melt. The breaker plate also supports the screen pack, develops head pressure (restricts flow), and converts the rotational motion of the melt to axial motion.

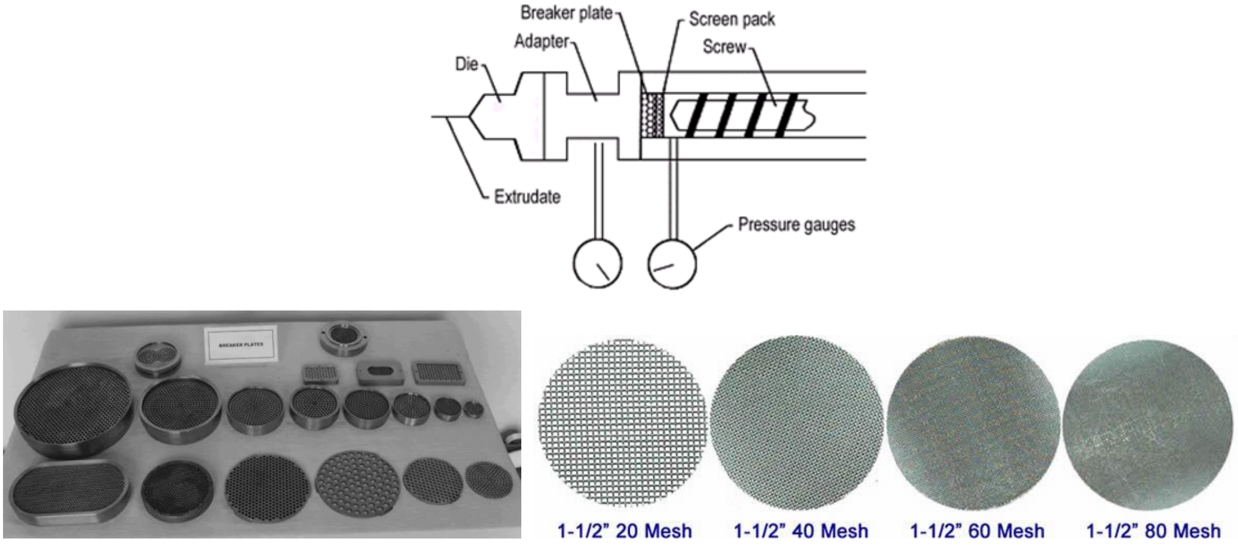


Fig 2.4 Breaker plate and screen packs.

The screen pack filters melt for contamination and gel particles, generate head pressure, and minimize surging (pulsing of the melt). Five or more screens are used in a typical screen pack; screens are rated by the number of holes per millimeter (or inch). The screens become finer as they approach the breaker plate. A coarse screen next to the breaker plate supports the finer screens and prevents the melt pressure from forcing them through the breaker plate. Although the selection of screen sizes depends on the material and extrusion process, increasing the number of screens or the mesh size increases the pressure developed during extrusion. Since screen packs become blocked by contaminants, they must be changed periodically.

A rupture disk is located in the extruder barrel just before the breaker plate. When the extruder pressure exceeds the disk’s rated value, the rupture disk opens, thereby reducing the pressure. Rupture disks are typically rated for 34.5, 51.7, and 70.0 MPa. They are required for operator safety.

Barrel heating and cooling

Barrels, dies, and die adapters are heated to bring them to operating temperatures and to maintain set temperatures during operation. To maintain constant temperatures, barrels must usually be cooled by fans (blowers) or water. Although fans remove heat slowly, they are inexpensive, and, thus, are the most commonly used. Each heating circuit (zone) of an extruder contains multiple heat bands, cooling fan(s), a temperature sensor, and a temperature controller. While the number of heating zones depends on the extruder's *L/D*, each zone contains 3500 to 4000 W of power. Temperature sensors are usually thermocouples located two-thirds into the barrel or die thickness; these "deep-well" sensors provide accurate temperature readings and are relatively insulated from air currents.

Extruder screws fit into the barrel and are supported by the thrust bearing. The screw's shank length fits into the thrust bearing, while the flighted length contacts the plastic. Extruder screws are specified by their outside diameter (*D*) and the *L/D*. In metering screws, the flighted section is divided into three zones: feed, transition or compression, and metering. The feed zone has a constant channel depth as does the metering zone. However, the channel depth gradually decreases in the transition zone. Since molten polymer requires less volume than the solid particles, the metering zone channel depth is shallower than the depth of the feed. The squeezing of the polymer is quantified by the compression ratio (CR):

$$\mathrm{CR} = \frac{V_{\text{first channel}}}{V_{\text{last channel}}} \cong \frac{H_{\text{first channel}}}{H_{\text{last channel}}}$$

where V is the channel volume and H is the channel depth.

Low compression ratios do not fully pack the solid particles, and so the melt will contain air bubbles. In contrast, high-compression ratios deliver too much polymer to the metering zone, and with polyolefins, produce melting problems in the transition zone. Thus, typical metering screws have compression ratios of 1.5:1 to 4.5:1.

Working of a single screw extruder

During extrusion, plastic particles flow from the hopper and into the feed throat of an extruder. Gravity is usually the driving force for solids conveying in hoppers. With pellets and some granules, this produces mass or hopper flow in which all the particles flow down the hopper to the feed throat. The feed throat is cooled to prevent plastic particles from melting at the base of the hopper, thereby forming a bridge [1].

Feeding Options

There are two basic feeding methods:

1. flood feeding and
2. starve feeding.

In flood feeding the feed hopper is filled to a certain level, the material flows to the extruder in mass flow (most of the time), and the extruder takes in as much material as it can bite off. The screw channel tends to be filled completely almost right away (Fig.2.5.a). As a result, in flood feeding the effective length of the screw is more or less the same as the flighted length of the screw.

In starve feeding the polymer is metered into the extruder by a feeding device (Fig.2.5 b). There is no accumulation in the hopper; the material instead drops directly into the screw channel, and the screw channel is only partially full at the feed opening. As the material is conveyed forward the screw channel will become completely filled some distance downstream of the feed.

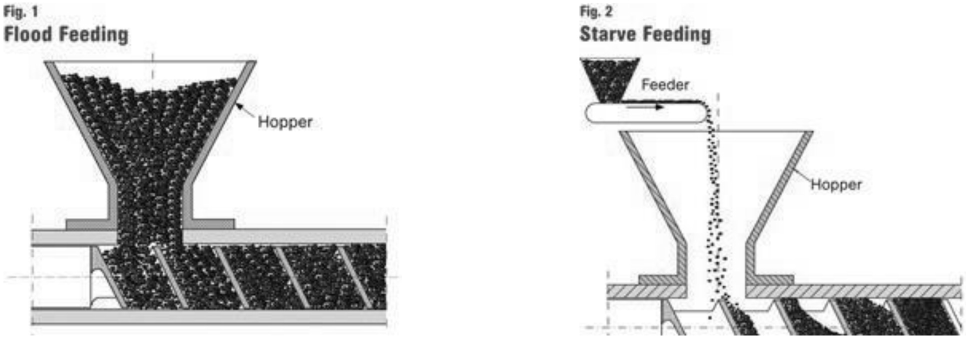


Fig 2.5 Feeding options in single screw extruder (a) - Flood feeding (b) Starve feeding

As a result, in starve feeding the effective length of the screw is less than the flighted length of the screw. An important advantage is that the effective screw length can be adjusted while the extruder is running. This allows broader process control than with flood feeding, where the effective length is not adjustable. Starve feeding is only beneficial if the extruder is long enough to achieve complete melting and effective mixing. Therefore, starve feeding generally will not give process improvements on short (25D long) extruders. Starve feeding requires a feeder, but it reduces motor load, melt temperature, and chances of agglomeration, bridging, and segregation in the hopper. Starve feeding allows a level of process optimization that is not possible with flood feeding [3].

Fig 2.6 Distribution of melted and solid materials in the screw (a) Starve feeding (b) Flood feeding

Mechanism of flow inside the extruder

As the plastic moves along the screw, it melts by the following mechanism. Initially a thin film of molten material is formed at the barrel wall. As the screw rotates, it scrapes this film off and the molten plastic moves down the front face of the screw flight. When it reaches the core of the screw it sweeps up again, setting up a rotary movement in front of the leading edge of the screw flight. Initially the screw flight contains solid granules but these tend to be swept into the molten pool by the rotary movement. As the screw rotates, the material passes further along the barrel and more and more solid material is swept into the molten pool until eventually only melted material exists between the screw flights [4]. In the metering zone of an extruder, the polymer is usually molten. The rotating screw pushes material along the walls of the stationary barrel creating drag flow. This drag flow provides the forward conveying action of the extruder, and, in the absence of a die, is effectively the only flow present. The addition of a die restricts the open discharge at the end of an extruder and produces a large pressure gradient along the extruder. Since the pressure is greatest just before the die, this head pressure creates two other flows, pressure flow and leakage flow. In pressure flow, the head pressure forces the melt to rotate in the channels of the extruder screw. Leakage flow occurs when the head pressure forces melt back over the flights of the screw. Since they both counter the forward motion of the melt, pressure and leakage flow are often lumped together as back flow. During normal extruder operation, drag flow conveys the polymer along the barrel walls, whereas pressure flow forces the material near the screw back toward the hopper [1]. Since the high pressure is at the end of the extruder the pressure flow will reduce the output. So the output from the extruder consisting of three components - drag flow, pressure flow and leakage [4].

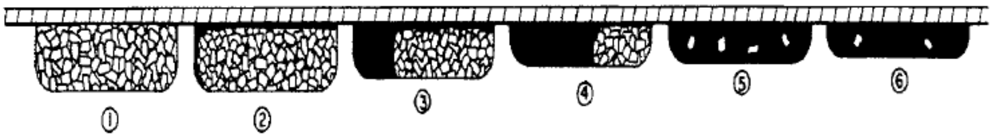


Fig 2.7 Melting model for a standard metering screw

Mixing elements

Since single-screw extruders provide relatively poor mixing, mixing elements are added to the screw's metering zone to improve mixing. Distributive mixing elements randomize the melt, while dispersive mixing elements provide shear (mechanical action) that reduces particle size. Although no element is purely distributive or dispersive, they are grouped according to the dominant mixing produced by the element.

Mixing pins are rows of metal pins inserted into the root diameter of a screw, while *slotted flights* are slots that are cut in the flights of the metering section of a screw. Both are simple and easily adapted to existing screws, but provide the potential for material stagnation and a limited degree of mixing. In addition, material flows back through the slotted flights; this increases residence time and provides an opportunity for degradation of heat and shear-sensitive materials. Some distributive mixing elements (Fig. 2.8) effectively mix, but provide no forward conveyance of the melt. These elements are usually incorporated into the last three or more channels of a screw. In the dulmage mixing section, the polymer is divided into 10 to 12 narrow channels, recombined, and then divided again. This produces excellent mixing in foam screws and for other applications. The saxton mixing section contains many minor flights on a helix angle that differs from that of the primary flights. The flights create new channels which divide the flow, and flow is recombined between segments of the mixing section. In contrast, with the pineapple mixing section, the polymer stream is divided and recombined as it flows around pinlike obstructions in the mixing element. For a cavity transfer mixing (CTM) section, an entire section is added to the end of the screw and extruder. Since cavities are present in both the screw and "barrel," melt is divided and recombined as it is transferred from screw to barrel cavities and back again.

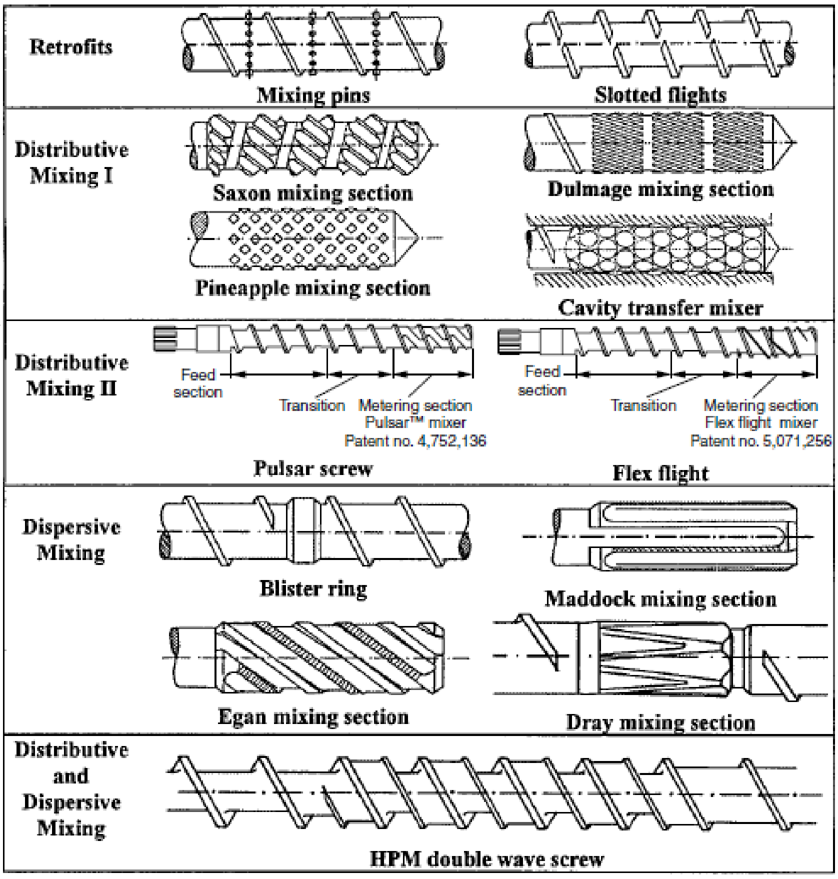


Fig 2.8 Selected mixing sections

The third group of mixing elements in Fig. 2.8 provides both distributive mixing and forward conveyance. In the pulsar mixing section (screw), the metering section of the screw is divided into alternating sections with either deep or shallow root diameters. Material is tumbled as it is forced from one section to the other. Since this produces good mixing without excessive shearing, the screw can be used for heat-sensitive polymers such as PVC. A flex flight mixing section incorporates a second flight in the screw’s metering zone; this creates two channels that vary in width. As channel width decreases, the material is forced over the second flight to produce both shearing and a tumbling action. The dispersive mixing elements in Fig. 2.8 include a blister ring, the Union Carbide or Maddock mixing section, and variants of the Maddock section. A blister ring is a cylindrical screw section with a clearance of 0.50 to 0.76 mm (0.020 to 0.030 in) that is added to the root diameter of the screw. As melt flows through the tight clearance, it is only sheared. This breaks up gel particles, but provides no mixing or forward conveyance. In contrast, a Maddock mixing element consists of axial grooves that are alternately open to the upstream and downstream sections of the screw. The grooves are separated by mixing and wiping lands with clearances of 0.64 mm (0.025 in) and 0.013 (0.005 in), respectively. As shown in Fig. 2.8 polymer flows into the former set of grooves. Since the axial downstream discharge is blocked, the polymer is forced over a mixing land and into the next channel. This channel is blocked upstream but open to downstream discharge. A wiping land ensures that the polymer exits the groove.

Maddock mixing sections, which are usually inserted one-third of the way down or at the end of the metering zone, reduces the size of gel particles and breaks up clumps of filler and pigment. However, they provide too much shear for heat- or shear-sensitive polymers, tend to increase melt temperature in some polymers, and do not convey the melt. The Egan and dray mixing sections represent improvements on the Maddock mixing section. In the Egan section, the grooves are placed at an angle to the screw axis, and the groove depth slowly decreases from the entry to the end of groove. While this reduces the pressure drop typical of Maddock sections, an optimized section design can actually generate pressure (and so increase output). With the dray mixing section, outlet channels are open at the start of the mixing section. Thus, not all material is forced over the mixing land; some just flows through the section. This reduces the pressure drop observed in Maddock sections, but provides a nonuniform shear on the polymer melt [1].

Twin Screw Extruders

Single-screw extruders are relatively similar in design and function. All single-screw extruders convey the polymer to the die by means of viscous drag (drag flow). While some variations occur in screw and extruder design, single-screw extruders generally provide high head pressures, uncontrolled shear, and a degree of mixing that relies on the screw design. Output depends on material properties, particularly the bulk properties (coefficient of friction, particle size, and particlesize distribution). In contrast, the design, principles of operation, and applications of twin-screw extruders vary widely. While the two screws are usually arranged side by side, the introduction of two screws produces different conveyance mechanisms, varied degrees of mixing, and controllable shear. The low head pressure generated by twin-screw extruders initially limited their use to processing of shear-sensitive materials, such as polyvinyl chloride, and to compounding. Although changes in design have permitted higher speeds and pressures[1], twin screw extruders have established a solid position in the polymer processing industry. The two main areas of application for twin screw extruders are profile extrusion of thermally sensitive materials (e. g., RPVC) and specialty polymer processing operations, such as compounding, devolatilization, chemical reactions, etc.

In twin screw extruder, the two screws are usually arranged side by side. The two screws are the key to understanding the conveyance mechanisms and probable applications of different twin-screw extruders.

Possible screw configurations -

Factor 1: direction of rotation - The screws may rotate in the same direction (corotating) or in opposite directions (counterrotating).

Factor 2: arrangement of screws the flights of the two screws may be separated, just touch (tangential), or intermesh to various degrees.

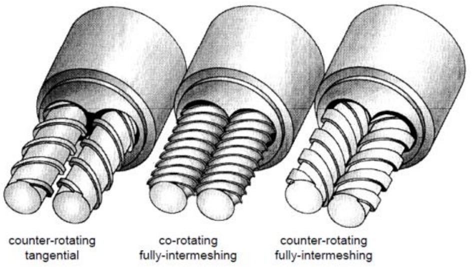
In addition, the flights of the two screws may be separated, just touch (tangential), or intermesh to various degrees. The flights of partially intermeshing screws interpenetrate the channels of the other screw, whereas the flights of fully intermeshing screws completely fill (except for a mechanical clearance) the channels of the adjacent screw.

While many configurations are possible, in practice the major designs are:

(1) nonintermeshing,

(2) fully intermeshing counterrotating, and

(3) fully intermeshing corotating twin-screw extruders



Nonintermeshing (separated or tangential) twin screws do not interlock with each other. The polymer is conveyed, melted, and mixing by drag flow. Since two corotating nonintermeshing screws would provide uncontrollable shear at the nip between two screw and little distributive mixing, they are not used commercially.

Counterrotating nonintermeshing

Counterrotating screws must rotate at the same rate to produce sufficient output. With matched flights, little plastic material is transferred between screws, however, substantial interscrew transfer occurs with staggered flights. As a result, counterrotating nonintermeshing twin-screw extruders provide good distributive mixing but little shear. The screws of commercial counterrotating tangential (CRT) twin-screw extruders are either matched or one screw is longer than the other. With the latter configuration, the single screw at the end of the extruder improves pressure generation. Thus, counterrotating nonintermeshing twinscrew extruders have been used for devolatilization, coagulation, reactive extrusion, and halogenation of polyolefins.

Intermeshing twin-screw extruders

With intermeshing twin-screw extruders, the flights of one screw fit into the channels of the other. Since the extruders are usually starve fed, the screw channels are not completely filled with polymer. By transferring some polymer from the channels of one screw to those of the other, the intermeshing divides the polymer in the channel into at least two flows. Thus, intermeshing twin-screw extruders provide positive conveyance of the polymer and improved mixing.

Counterrotating intermeshing twin-screw extruders

In counterrotating, intermeshing twin-screw extruders, a bank of material flows between the screws and the barrel wall. The remainder is forced between the two screws and undergoes substantial shear.

With little intermeshing, drag flow between the screws is greater than that at the barrel walls. However, for the commercial fully intermeshing screws, most material flows along the screws in a narrow channel (C chamber) and is subject to relatively low shear. Consequently, the degree of mixing in counterrotating, intermeshing twin-screw extruders depends on the degree of intermeshing and screw geometry. Increasing the distance between the screws increases flow between the screws and permits effective distributive mixing. However, increased screw separation only decreases the shear rate in the nip, and hence reduces dispersive mixing. Since screw length and geometry are also used to prevent excessive shearing, melting in these extruders is limited, and most of the heat transferred to the polymer is conducted from the barrel. This mechanism provides very sensitive control over the melt temperature. With good temperature control and the low shear, these extruders are well suited for compounding and for extrusion of rigid poly(vinyl chloride). Typically, high-speed (200- to 500-r/min69) extruders are employed for compounding, whereas low-speed (10- to 40-r/min69) machines are used for profile extrusion. Conical twin-screw extruders with their tapering screws (as shown below) are utilized almost exclusively for chlorinated polyethylene and rigid poly(vinyl chloride).

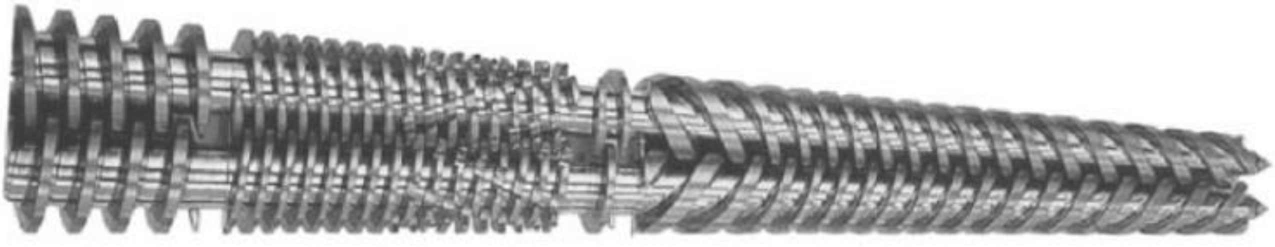
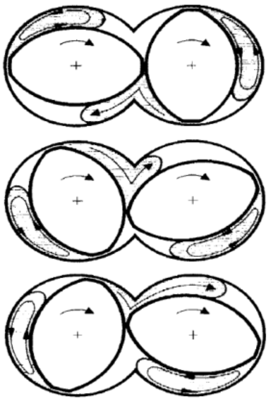


Fig. 2.9 Conical twin-screw extruders with their tapering screws

Corotating fully intermeshing twin screw extruder

Corotating fully intermeshing twin screws are self-wiping. Thus, they tend to move the polymer in a figure-eight pattern around the two screws, as shown in below figure. Typically, a screw flight pushes the material toward the point of intersection between the two screws. Material is then forced to change its direction through a large angle, which mixes the material. Very little material is able to leak between the screws. Finally, the material is transferred from one screw to the next. The flow pattern provides a longer flow path for the material, and hence, the longer residence time of corotating extruders. Mixing elements, such as kneading blocks, are not fully self-wiping, but are usually incorporated to improve melting and mixing. However, unlike counterrotating screws, the shear between the corotating screws is relatively mild. Consequently, the combination of longer flow paths, more uniform shear, and self-wiping conveying elements make corotating intermeshing twin screws well suited to mixing and compounding applications.



Flow pattern in a corotating, fully intermeshing twin-screw extruder.

Comparison of Single and Intermeshing Twin-Screw Extruders

Parameter	Single screw	Corotating twin screw	Counterrotating twin screw
Conveyance	Drag flow	Positive conveyance	Positive conveyance
Mixing efficiency	Poor	Medium-high	Excellent
Shear	High (depends on *N*)	Screw design dependent	Screw design dependent
Self-cleaning	No	Yes	Partially
Energy efficiency	Low	Medium	High
Screw speed (r/min)	50–300	25–300	50–100

Process Control Variables

Extruder instrumentation is one of the most critical components of the entire machine. An important reason for this is that the internal workings of the extruder are totally obscured by the barrel and the die. In many cases, the only visual observation that can be made is of the extrudate leaving the die. When a problem is noticed in the extrudate, it is difficult to determine the source and location of the problem. Instrumentation makes it possible to determine what is happening inside the extruder. One can think of instrumentation as “the window to the process.”

Good instrumentation enables a continuous monitoring of the “vital signs” of the extruder. These vital signs are pressure, temperature, power, and speed. These important process parameters need to be measured for process control, but they are also of vital importance in troubleshooting. Troubleshooting is only possible with good instrumentation. At the very minimum, one needs to know pressures, screw speed, and temperatures in order to properly diagnose an extrusion problem. A minimum set of instrumentation should include:

1. Diehead pressure before and after screen pack
2. Rotational speed of the screw
3. Temperature of polymer melt at the die
4. Temperatures along barrel and die
5. Cooling rate at each heat zone
6. Power consumption of each heat zone
7. Power consumption of the drive

8. Temperature of cooling water in feed housing
9. Flow rate of cooling water in feed housing

The parameters above relate just to the extruder. However, there are many more process parameters for the entire extrusion line and they, depend on the line's specific components. Important parameters for any extrusion line are:

1. Line speed
2. Dimensions of the extruded product
3. Cooling rate or cooling water temperature
4. Line tension

Many other factors can influence the extrusion process, such as ambient temperature, relative humidity, air currents around the extruder, and plant voltage variations among others.

Good instrumentation allows problems to be detected early before becoming more severe and causing substantial damage to the extruder hardware or to the extrudate quality. It also allows process characterization for process development and optimization. It is further important for production control and record keeping, and it provides a means of interfacing the extruder to a computer.

Most Important Parameters

The most important process parameters are melt pressure and temperature. They are the best indicators of how well or how poorly an extruder functions. Process problems become obvious from melt pressure and /or temperature readings. Melt pressure and temperature are good indicators of how the extruder is functioning.

Pressure Measurement

The Importance of Melt Pressure

Measurement of melt pressure is important for two reasons:

1. Process monitoring and control
2. Safety

The diehead pressure in the extruder determines the output from the extruder. It is the pressure necessary to overcome the resistance of the die. When the diehead pressure changes with time, the extruder output correspondingly changes and so do the dimensions of the extruded product (Fig. 4.1). As a result, when we monitor how the pressure varies with time, we can see exactly how stable or unstable the extrusion process is.

It is best, therefore, to plot pressure with a chart recorder or better, to monitor the variation of pressure with a computer data acquisition system. A simple analog or digital display of pressure is much less useful.

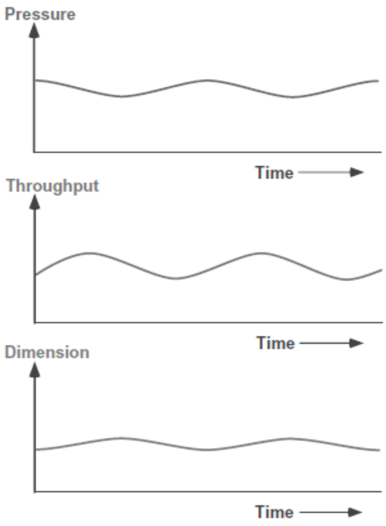


Figure 4.1 Pressure, throughput, and dimension as a function of time

It is also critically important to measure pressure in the extruder to prevent serious accidents that can happen when excessively high pressures are generated. *The very high pressures generated in the extruder can cause an explosion.* The barrel can crack open under excessive pressure or the die may be blown from the extruder. Both situations are extremely dangerous and should be avoided. All extruders should have an over-pressure safety device, such as a rupture disk or a shear pin in the clamp holding the die against the extruder barrel. Even with such an over-pressure safety device, the extruder should have at least one melt pressure measurement, in order to overcome malfunctioning or disabled over-pressure devices. Pressure can build up very quickly without warning and cause a catastrophic explosion. When monitoring pressure, it is a good idea to use an automatic shutoff when the pressure reaches a critical value. In pressure measurements, it is important to determine the absolute level of pressure, but it is equally important, if not more important, to determine changes in pressure with time. In most cases, pressure variation correlates closely with variation in the extruded product. Since high frequency (cycle time less than one second) pressure fluctuations are quite common in extrusion, a fast response measurement is important.

Different Types of Pressure Transducers

Pressure measurement on early extruders was done with grease-filled Bourdon gauges. The reliability of these gauges was not very good. As a result, Bourdon gauges are hardly used anymore.

Nowadays there are a number of different pressure transducers. The most common ones in extrusion are the strain gauge transducer and the piezo-resistive transducer.

In a strain gauge pressure transducer a strain gauge is bonded to a diaphragm. The melt pressure deforms the diaphragm and the strain gauge measures the deformation of the diaphragm; These units generally have good response and resolution. Since the strain gauge cannot be exposed to high temperatures, it is placed away from the heated polymer/ barrel environment. Therefore, a mechanical or hydraulic coupling is used to transmit the deflection of the diaphragm to the strain gauge.

The strain gauge transducer can be either a capillary or a pushrod transducer. In these transducers, there are two diaphragms, one in contact with the plastic melt and the other some distance away from the hot plastic melt. The connection between the first and second diaphragm is hydraulic in the capillary type and a pushrod in the pushrod type;

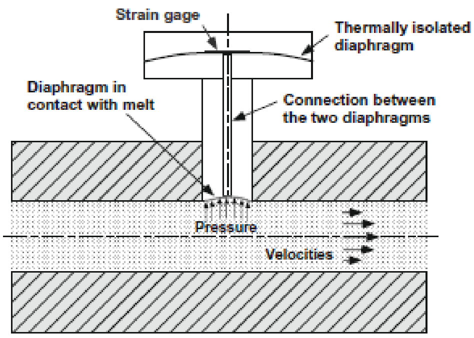


Figure 4.2 Principle of the strain gauge transducer

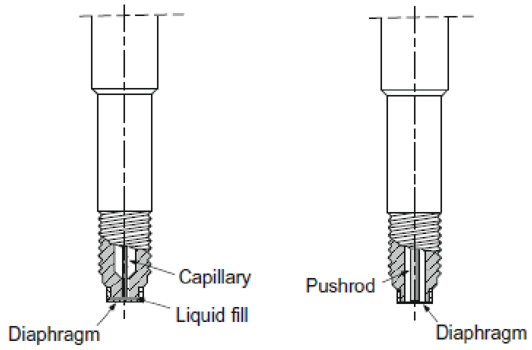


Figure 4.3 Capillary (left) and pushrod type (right) pressure transducer

The capillary transducer has fair robustness, fair temperature sensitivity, and fair dynamic response. The total measurement error varies from 0.5 to 3% depending on the quality of the transducer. The pushrod is similar to the capillary transducer, except that it tends to have poor temperature sensitivity and poor total error.

Other pressure transducers use a piezoelectric element. A piezoelectric material has the ability to transform a very small mechanical deformation (input signal) into an electric output signal (voltage or current) without any external electric power supply. Quartz pressure transducers have been developed to measure large pressures in high temperature polymer melts. The absence of a membrane allows a very robust construction. Piezoelectric pressure transducers can be designed in a very compact package. The required deflection to obtain a pressure reading can be very small because of the high sensitivity of the piezoelectric element. The deflection is generally measured in microns (μm); full pressure can be reached with a deflection of less than 10 μm. The temperature range is primarily determined by the insulation. Transducers with ceramic insulation can be exposed to temperatures as high as 350°C. The more common PTFE insulation allows temperatures up to 240°C. The linearity of these transducers is better than 1%. The sensitivity is in the range of a few pC/ bar at pressures of up to 7500 bar (about 750 MPa or 110,000 psi). One of the main advantages of piezo pressure transducers is their outstanding dynamic response. One of the main drawbacks of piezoelectric pressure transducers is that they cannot measure steady pressure accurately because the signal decays. Therefore, piezoelectric pressure transducers are limited to applications where the pressure changes over relatively short time frames (on the order of a few seconds or less).

Some transducers use piezo-resistive semiconductors implanted into a small chip. The resistance of piezo-resistive materials changes with stress or strain. When the chip is bonded to a pressure-sensing diaphragm, the change in resistance can be measured with a Wheatstone bridge. The piezo-resistive element can provide a repeatable signal that is proportional to the pressure against the diaphragm. Piezo-resistive pressure transducers offer a number of advantages. The transducer is quite robust because of the relatively thick diaphragm. There is no liquid fill inside the transducer; as a result, there is no concern about leakage of mercury. The natural frequency of piezo-resistive transducers is about three orders of magnitude better than strain gauge type transducers. As a result, the dynamic response of piezo-resistive transducers is very good compared to that of strain gauge transducers.

Optical pressure transducers can offer some important advantages. The sensor can be used to temperatures as high as 600°C, in some cases even higher. Even though this type of transducer is not commonly used in the extrusion industry.

Temperature Measurement

Temperature measurement occurs at various locations of the extruder: along the extruder barrel, in the polymer melt, and at the extrudate once it has emerged from the die. The choice of the type of temperature measurement will depend on what is being measured and where.

Methods of Temperature Measurement

Temperature can be measured with resistive temperature sensors, thermocouple temperature sensors, and radiation pyrometers. There are two types of resistive temperature sensors (RTD): the conductive type and the semiconductor type. Both operate on the principle that the resistance of sensor material changes with temperature. The conductive-type temperature sensor (RTD) uses a metal element to measure temperature. The resistance of most metals increases with temperature; thus, by measuring resistance, one can determine the temperature. Platinum is used where very precise measurements are required and where high temperatures are involved.

The semiconductor type sensor utilizes the fact that the resistance of a semiconductor decreases with temperature. The most common type of semiconductor temperature sensor is the thermistor. Because of their small size, thermistors can be used where other temperature sensors cannot be used.

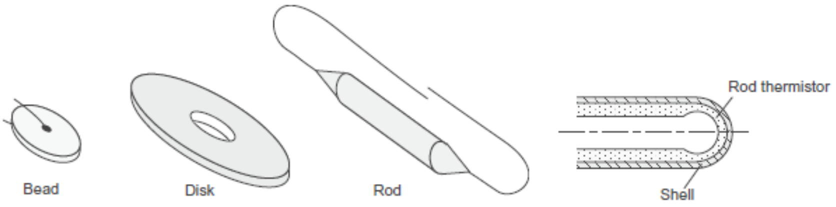


Figure 4.9 Thermistor

Thermocouple (TC) temperature sensors are also known as thermoelectric transducers; sensing junction) and terminated at the other end by terminals (the reference junction) maintained at constant temperature (reference temperature). When there is a temperature difference between sensing and reference junctions, a voltage is produced. This phenomenon is known as the thermoelectric effect. The amount of voltage produced depends on the temperature difference and the metals used.

One of the most common TCs is the iron-constantan TC.

For temperature measurements on the emerging extrudate, contacting-type measurements are not suitable because of damage to the extrudate surface. For non-contacting temperature measurements, infrared (IR) detectors can be used. The intensity of the radiation depends on the wavelength and the temperature of a body. Non-contact IR thermometers can be used to determine the temperature of the plastic after it leaves the die. IR sensors can also be used to measure the melt temperature inside the extruder or die;

Barrel Temperature Measurement

The barrel temperature needs to be measured to provide information on the axial barrel temperature profile and to provide a signal for the controllers of the barrel heaters and cooling devices. The temperature should be measured as close as possible to the inner barrel surface. The worst possible location of the temperature sensor would be in the barrel heater itself. The major drawback of this approach is that one controls the heater temperature and not the temperature of the polymer in the extruder barrel. Some extruders are equipped with a combination of deep-well and shallow-well temperature sensors to improve the temperature control of the extruder.

Stock Temperature Measurement

The measurement of the temperature of the polymer melt is of major importance. Measurement of stock temperatures along the extruder barrel is difficult because of the rotation of the screw. To measure stock temperatures, the temperature sensor has to protrude into the polymer. The temperature sensors cannot be placed in the barrel because the protruding sensor would be damaged by the screw flight.

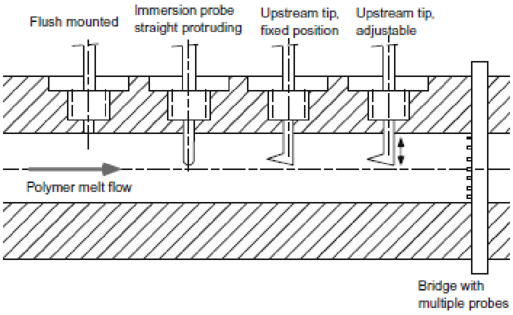


Figure 4.16 Various melt temperature sensor configurations

Infrared Melt Temperature Measurement

IR probes that can be mounted in an extruder barrel or die are used to measure a more or less average stock temperature over a certain depth of the polymer, about 1 to 5 mm for most unfilled polymers. The actual depth of the measurement is determined by the optical properties of the polymer melt, in particular the transmittance. The measurement is affected by variations in the consistency of the polymer melt. Thus, when fillers, additives, or other polymeric components are added, the temperature readings will be affected. An important advantage of the IR stock temperature measurement is the rapid response time, which is about ten milliseconds. The response of conventional melt thermocouples is several orders of magnitude slower. This means that rapid temperature fluctuations can be made visible with IR allowing a more detailed study of the dynamic behavior of extruders and injection molding machines.

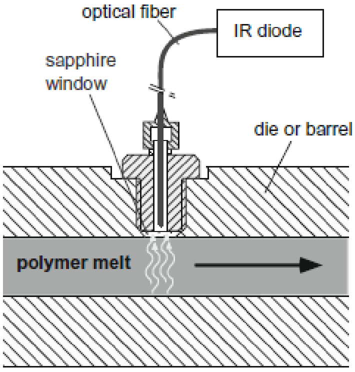


Figure 4.17 An infrared melt temperature sensor

Other Measurements

Pressure and temperature are two process parameters of major importance. There are, however, various other parameters such as

1. Power Measurement
2. Rotational Speed
3. Extrudate Thickness
4. Extrudate Surface Conditions

Temperature Control

The dynamic behavior of an extruder is significantly determined by the temperature control system on the extruder. It is, therefore, important to understand the basic characteristics of the various temperature control systems. Most control systems are closed-loop or feedback systems. The variable to be controlled is measured and this information is sent to a control unit. From the control unit a signal is sent to an actuator that adjusts the process such that the control variable is as close as possible to the desired value, the setpoint. Feedback control systems are commonly used in extruders. There are basically two ways to keep the level of a variable within certain limits:

1. the on-off method and
2. the modulating or continuous adjustment method.

The on-off control is probably the simplest type of automatic control.

On-Off Control

In on-off control of temperature, the power to the extruder is full-on when the measured temperature is below the setpoint and completely off when the measured temperature is above the setpoint.

Proportional Control

One of the drawbacks of on-off control is that there are only two power input levels possible: fully on and fully off. In essentially all practical cases, the power level required to maintain a certain temperature will be somewhere between 0 and 100% power. Therefore, application of on-off control will invariably lead to fluctuations of the actual temperature. To avoid this problem, a control system is needed that can adjust the power input level to the exact level required to maintain the temperature at the setpoint. Only then is it possible to maintain a steady temperature [2].

1. Proportional-Only Control
2. Proportional and Integral Control
3. Proportional and Integral and Derivative Control

Viscoelastic properties and die swell

The word viscoelastic is derived from the words "viscous" + "elastic"; a viscoelastic material exhibits both viscous and elastic behaviour.

Extrusion Instabilities

Variations in extruder performance is perhaps the most frequent problem encountered in extrusion. One possible reason for the frequent occurrence of instabilities is the fact that they can have a large number of causes, some of which are:

ƒ.Bulk flow problems in the feed hopper
ƒ.Solids conveying problems in the extruder

ƒ.Insufficient melting capacity
ƒ.Solid bed breakup
ƒ.Melt temperature non-uniformities in the die
ƒ.Barrel temperature fluctuations
ƒ.Screw temperature fluctuations
ƒ.Variations in the take-up device
ƒ.Melt fracture/shark skin
ƒ.Variations in screw speed
ƒ.Barrel wear/screw wear
ƒ.Insufficient mixing capacity
ƒ.Very low diehead pressure
ƒ.Insufficient pressure-generating capacity

A prerequisite for stable extrusion is a good extruder drive, good temperature control system, good take-up device, and most importantly, a good screw design. Probably more instabilities result from improper screw design than from any other cause. However, a change in screw design is often only considered as the very last option.
The extruder drive should be able to hold the screw speed constant to about 0.1% or better; the same holds true for the take-up device. However, this is not always the case on actual extrusion lines. The extruder should be equipped with some type of proportioning temperature control, preferably a PID-type control or better. On-off temperature control is inappropriate for most extrusion operations.

Intermeshing Co-Rotating Extruders (for reference only)

There are two types of intermeshing co-rotating extruders: the low speed extruder and the high speed extruder. The two machines are different in design, in operating characteristics, and in areas of application. The low speed co-rotating twin screw extruder is primarily used in profile extrusion, while the high speed extruder is primarily used in compounding.

Closely Intermeshing Extruders

The low speed extruder has closely intermeshing screw geometry where the flight profile fits closely into the channel profile, i.e., a conjugated screw profile. A typical screw geometry of the closely intermeshing co-rotating (CICO) twin screw extruder is shown in Fig. 2.9

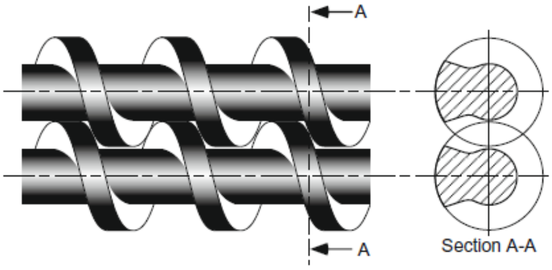


Figure 2.9 Screw geometry of a CICO extruder

The conjugated screw profile shown in Fig. 2.9 appears to form a good seal between the two screws. However, a cross-section through the intermeshing region, shown in Fig. 2.10, reveals the presence of relatively large openings between the channels of the two screws. Therefore, the conveying characteristics of the CICO extruder are not as positive as those of a closely intermeshing counter-rotating extruder (CICT);

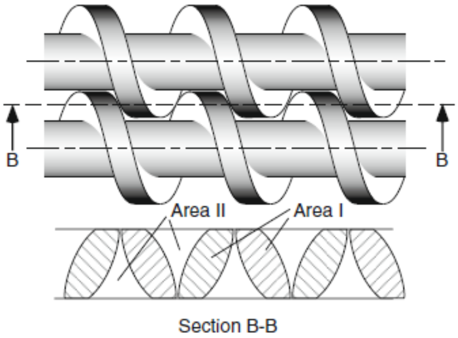


Figure 2.10 Cross-section through the intermeshing region of a CICO extruder

The co-rotating twin screw extruder has a sliding type of intermeshing as shown in Figure 2.11.

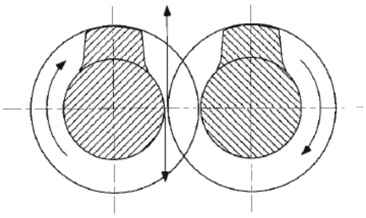


Fig. 2.11 Sliding type of intermeshing in co-rotating twin screw extruders

The screw velocities in the intermeshing region are in opposite directions. Therefore, material entering the intermeshing region will have little tendency to move through the entire intermeshing region unless the flight flank clearance is quite large; this situation is shown in Fig. 2.11(a).

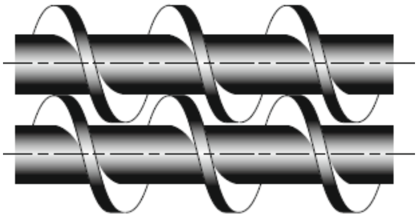


Figure 2.11(a) Intermeshing region with a large flank clearance

Because of the relatively large open areas between the channels, material entering the intermeshing region will tend to flow into the channel of the adjacent screw. The material will move in an open figure-eight pattern, as shown in Fig. 2.11 (b), while at the same time moving in the axial direction.

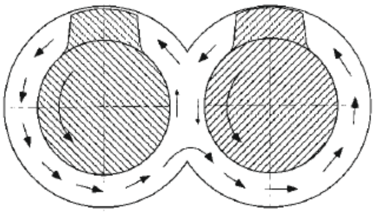


Figure 2.11 (b) Movement of material in open figure-eight pattern

The material close to the passive flight flank cannot flow into the channel of the adjacent screw because it is obstructed by the flight of the adjacent screw. The material, therefore, will undergo a circulatory flow as shown in Fig. 2.12.

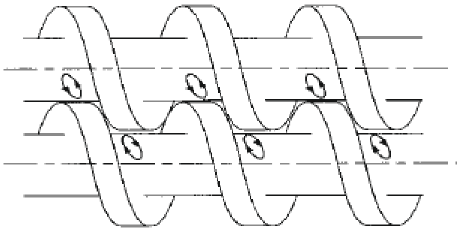


Figure 2.12 Circulatory flow at the passive flight flank

This material fraction will move forward at axial velocity va:

$$v_a = \pi D N \tan\varphi$$

The obstructed material fraction will contribute to the positive conveying characteristics of the extruder. If the obstructed area (Area I in Fig. 2.10) is large relative to the open area (Area II in Fig. 2.10), then the conveying characteristics will be quite positive. If the open area is large relative to the obstructed area, then the positive conveying characteristics will be considerably reduced, resulting in a wide residence time distribution (RTD) and a more pressure-dependent throughput. CICO extruders have relatively positive conveying characteristics because their screw geometry is such that the open area is small relative to the obstructed area. The sliding type of intermeshing will result in high pressure regions at the point where the material enters the intermeshing region; this is shown in Fig. 10.8.

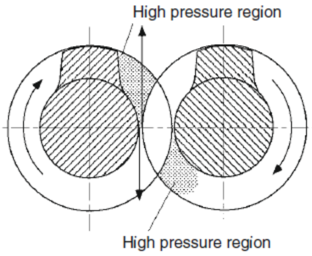


Figure 2.13 High pressure regions at the entrance to the intermeshing region

The pressure build-up occurs primarily because of the reduction in cross-sectional area of the flow channel as the material enters the intermeshing region. Pressure build-up also occurs because of the change in flow direction that occurs as the material enters the intermeshing region. Obviously, the pressure build-up will be most severe when the open area is small compared to the obstructed area, which is the case in CICO twin screw extruders. These high pressure regions will result in lateral forces on the screws trying to push the screws apart. These separating forces will increase with screw speed. Clearly, the separating forces should not be as large as to cause contact between the screws and barrel, since this will result in severe wear. Therefore, CICO extruders have to run at low speed in order to avoid large pressure peaks in the intermeshing region.

Self-Wiping Extruders

High speed co-rotating extruders have a closely matching flight profile, as shown in Fig. 2.14.

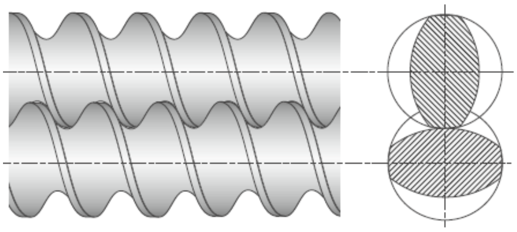


Figure 2.14 Flight geometry in CSCO extruders

There is considerable openness from one channel to the adjacent channel. This is obvious both from the top view of the screws shown in Fig. 2.14 as well as from the cross-section through the intermeshing region, shown in Fig. 2.15.

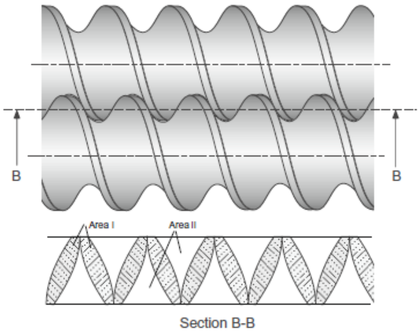


Figure 2.15 Cross-section through the intermeshing region in CSCO extruders

Thus, the open area II is large relative to the obstructed area I. Therefore, there is relatively little tendency for large pressure peaks to form in the intermeshing region. The screws can therefore be designed with relatively small clearances between the two screws; the screws are then closely self-wiping. Twin screw extruders of this design are generally referred to as closely self-wiping co-rotating extruders (CSCO).

Since the tendency to develop large pressure peaks in the intermeshing region is quite small with CSCO extruders, they can run at high speeds, as high as 1400 rpm. This is made possible by the relatively large open area in the intermeshing region. However, this geometrical characteristic also results in a relatively non-positive conveying characteristic with a corresponding wide RTD and pressure-sensitive throughput. These machines, therefore, are not well suited for direct profile extrusion. A large fraction of the material will follow the figure-eight flow pattern.

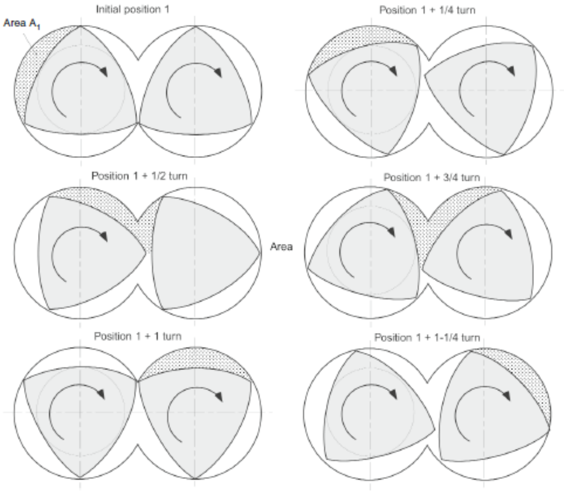


Fig 2.16 Material transfer in a CSCO extruder

Non-Intermeshing Twin Screw Extruders

Non-intermeshing twin screw extruders are double screw machines where the centerline distance between the screws is larger than the sum of the radii of the two screws. Commercial examples of non-intermeshing twin screw extruders are counter-rotating (NOCT extruders). The conveying in NOCT extruders is similar to that in a single screw extruder. The main difference is the fact that there is a possibility of exchange of material from one screw to another. If the apex area (see Fig. 2.17) is zero, the NOCT extruder behaves as two single screw extruders.

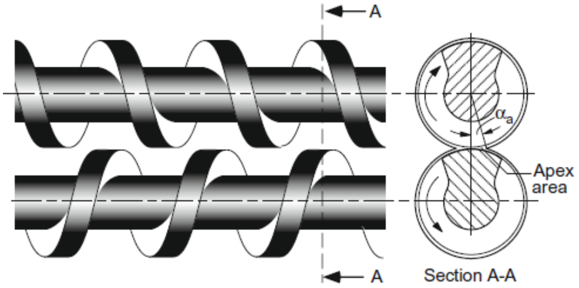


Figure 2.17 NOCT extruder geometry

Because of the non-zero apex area, the output of the NOCT extruder will be less than twice the output of a single screw extruder with the same screw diameter. The NOCT extruder has less positive conveying characteristics than a single screw extruder. As a result, however, it has better backmixing characteristics than a single screw extruder. Therefore, the NOCT extruder is primarily used in blending operations, devolatilization, chemical reactions, etc. The particular conveying characteristics of the NOCT extruder make it undesirable for profile extrusion. In one commercial example of a NOCT extruder, the screws are of different length such that the last section of the extruder has a single screw discharge. This design is shown in Fig. 2.18.

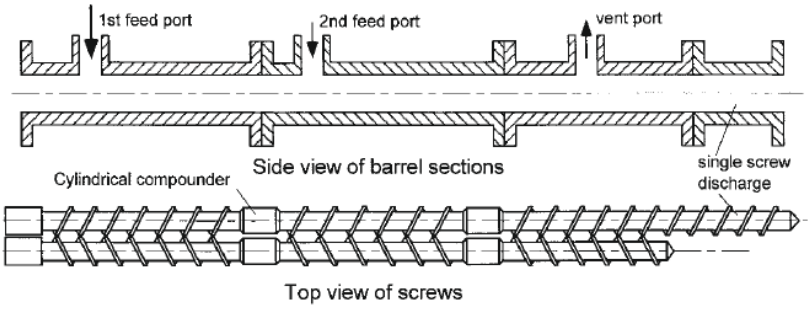
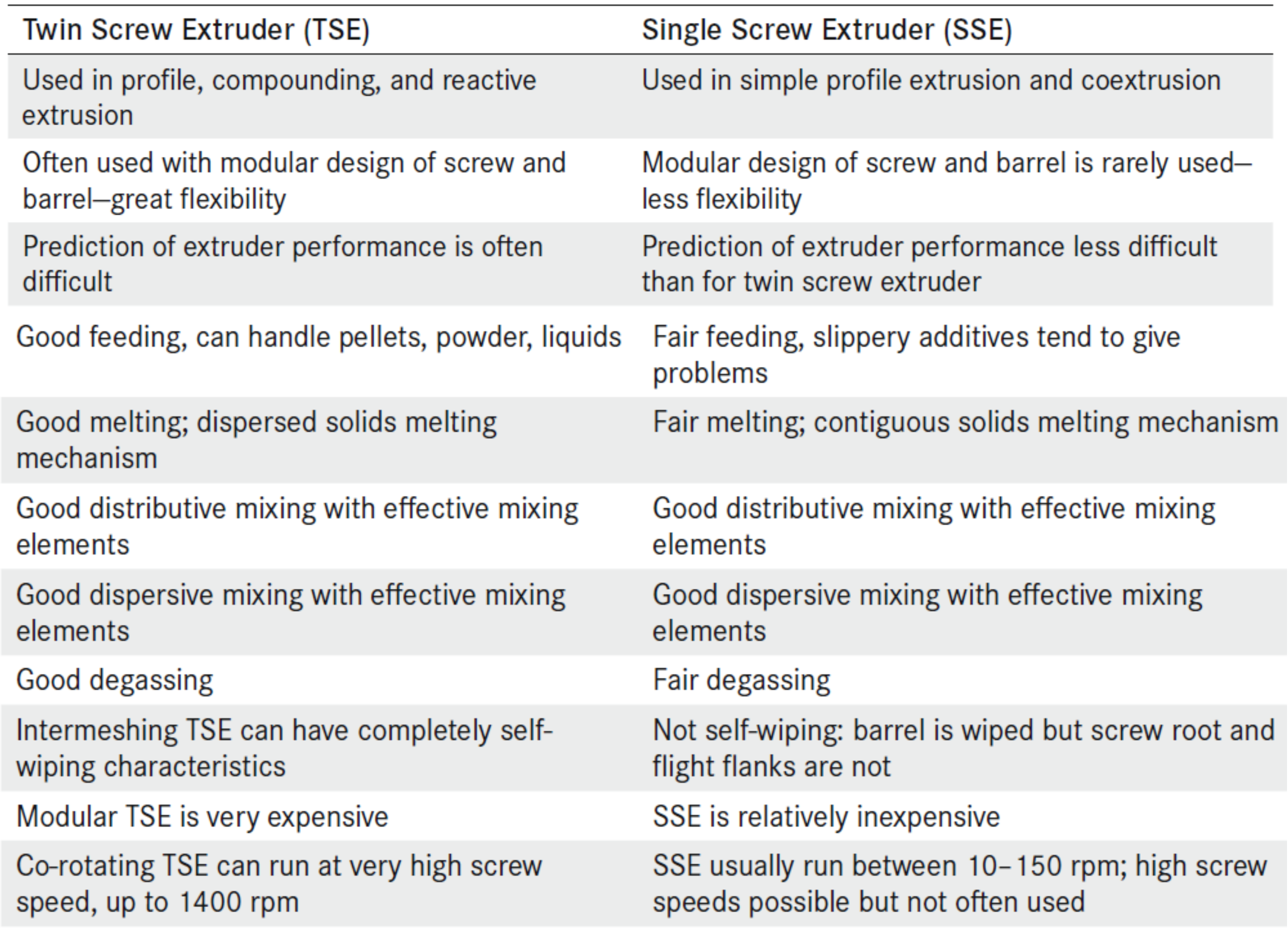


Figure 2.18 NOCT extruder with unequal screw lengths

Two advantages of this configuration are improved pumping characteristics and a thrust load on one screw only. The thrust load on the secondary (short) screw is very small. Thus, the thrust bearing design is greatly facilitated. A disadvantage of this construction is a non-symmetrical conveying process with a chance of hang-up of material in the transition region.

Table 2.1 Comparison of Twin Screw and Single Screw Extruder



Twin Screw Extruder (TSE)	Single Screw Extruder (SSE)
Used in profile, compounding, and reactive extrusion	Used in simple profile extrusion and coextrusion
Often used with modular design of screw and barrel—great flexibility	Modular design of screw and barrel is rarely used—less flexibility
Prediction of extruder performance is often difficult	Prediction of extruder performance less difficult than for twin screw extruder
Good feeding, can handle pellets, powder, liquids	Fair feeding, slippery additives tend to give problems
Good melting; dispersed solids melting mechanism	Fair melting; contiguous solids melting mechanism
Good distributive mixing with effective mixing elements	Good distributive mixing with effective mixing elements
Good dispersive mixing with effective mixing elements	Good dispersive mixing with effective mixing elements
Good degassing	Fair degassing
Intermeshing TSE can have completely self-wiping characteristics	Not self-wiping: barrel is wiped but screw root and flight flanks are not
Modular TSE is very expensive	SSE is relatively inexpensive
Co-rotating TSE can run at very high screw speed, up to 1400 rpm	SSE usually run between 10–150 rpm; high screw speeds possible but not often used

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