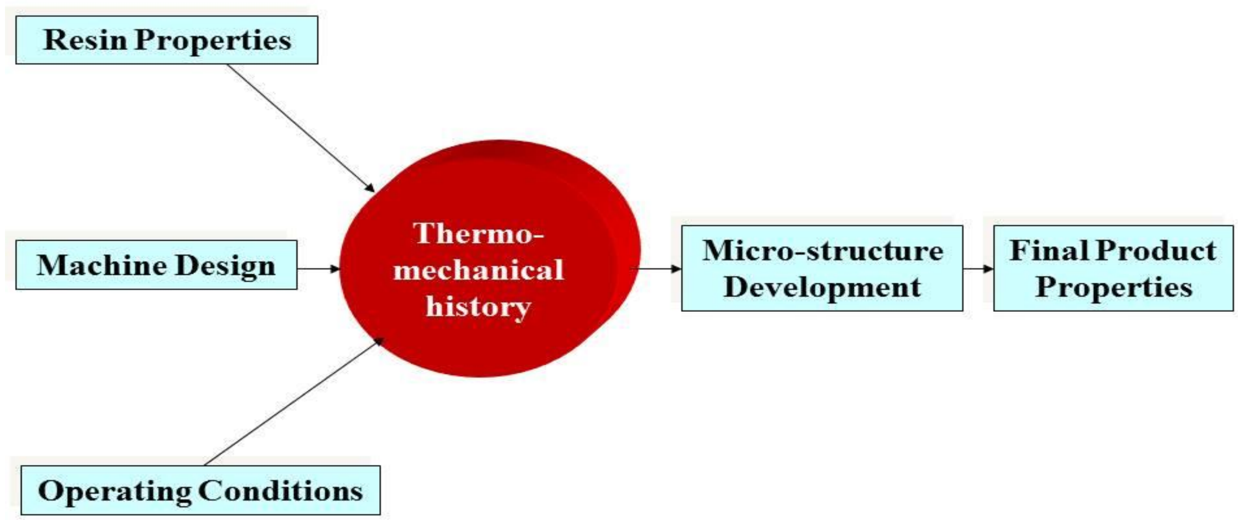
Polymer Processing Overview



Polymer processing emerged as a separate, identifiable engineering discipline in the late 1950s and 1960s. The reasons for this exciting development can be attributed to important advances that took place in the late 1980s and 1990s. Plastics processing faces challenges and opportunity to develop techniques and needs with materials in terms of intellectuality and modernization. Some of the important developments are:

- Improvement in polymer properties to suit different applications
- Progress in engineering plastics
- Scientific compounding to create copolymers, block copolymers, graft copolymers, etc.
- Computer revolution in plastics manufacturing and processing technology
- Instruments to measure the polymer properties.

Plastics processing provides different methods to produce different products with the development of thermoplastic materials. Thus, focus on plastics processing is characterized with technologies, knowledge, and hi-tech involvement.

In the thermoplastic materials, production and processing occur in the molten state. Knowledge of flow behavior of the material is essential for all forms of production and processing. Also, polymer processing is a multidisciplinary field that fuses with polymer physics and polymer chemistry.

Plastic materials are the most versatile material and contribute in several aspects and in their initial stage as powder or granules. Plastic processing techniques are used to utilize the powder or granules for finished parts. The ability of thermoplastics to melt and re-harden has been exploited in many different processing methods.

Temperature and pressure are known to be two of the most influential variables in the rheological characteristics of polymer melt in plastics processing. It has long been realized by those in practice that the flow behavior of molten polymer is highly dependent upon these two variables.

Plastics processing can shape material and improve its properties in terms of end products produced. In plastics processing, material undergoes a common practice of mixing, melting, plasticizing, shaping, and finishing. Thermoplastic materials have sufficient melt strength to remain integral during processing.

Plastics are available in the form of pellets, granules, and powder which can be extruded, blow molded, injection molded or rotational molded, to finished products. Knowledge of plastics to production to their end use properties has become important in view of material development.

Major processing methods like extrusion, injection molding, thermoforming, and rotational molding have been subjected to significant technological progress.

The choice of processing method has both technical and economical aspects between material and end product properties.

Plastics processing requires external heating to melt and the resulting frictional heat impacts finished product quality. The plastic melt is highly viscous during processing. The polymer melt depends on molecular weight, molecular weight distribution, chain branching, shear rate, and shear stress.

Plastics shrink in molds during the cooling process. Shrinkage for amorphous plastics is less than for semi-crystalline plastics. Shrinkage is larger in the thickness direction than other directions. Orientation of plastic occurs in the direction of flow.

Plastics processing requires the knowledge fundamentals of the raw material, additives, process control, and finally the product properties required to the finished end product. Today, polymer contains a package of ingredients to modify its properties while processing, or at its end product stage to create a new one.

In thermoplastics, processing techniques can be classified into either batch or continuous process. Batch processes include injection molding, thermoforming and rotomolding. Extrusion of plastics is a continuous process. However, blow molding is available both in batch and continuous process. In these days, online continuous thermoforming machines are available along with extrusion process.

As the scientific techniques become available, the plastics processing is quickly incorporating the changes. However, new solutions pose new problems so these continue to be challenges to overcome. Troubleshooting helps to solve the problem at the root and increase the production efficiency during processing.

Properties and Processing

Today, a great deal of interest is placed on the use of plastics because of lower cost, and because they are a major source for industrial products and abundantly available. Plastic also has electric resistance, lower thermal conductivity, ability to come in an unlimited range of colors, and excellent surface finish.

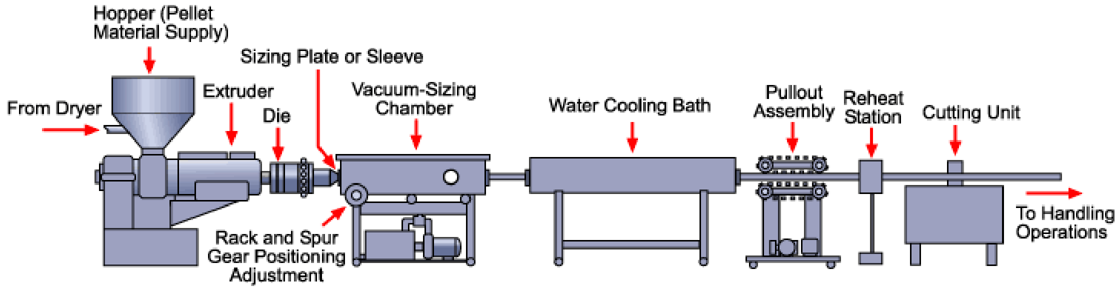
Physical properties of the polymer are primarily dependent on the crystalline, amorphous or molecular orientation of material. This morphology is in terms dependent on thermal and mechanical treatment during processing. The materials physical properties that help in processing are melt temperature (Tm), degradation temperature (Td), glass transition temperature (Tg), processing temperature, and density.

Plastics materials undergo different and complicated thermo-mechanical processes and experience the significant change in their rheological, mechanical, and transport properties due to large pressure variations and rapid cooling. Semi-crystalline plastics undergo a phase transition during heating or cooling near the melting point as demonstrated for PS and polyacetal. The reason for the behavior of semi- crystalline material is due to higher and necessary processing temperature during injection molding. Amorphous materials generally provide better weld line strength than semi- crystalline materials, and a polymer material with higher flow rate may allow better packing for a stronger weld line.

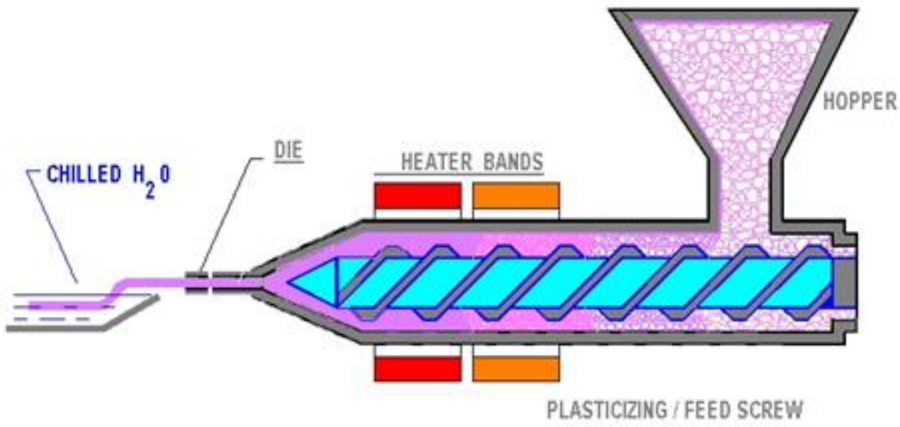
Polymer properties are strongly influenced by :

- Molecular weight (MW) of the material
- Molecular weight distribution (MWD)
- Degree of branching

Extrusion Process



In this process, a continuous flow of molten material is forced through a die. The shape of the final product is determined by the shape of the die opening. Typically, thermoplastic molding power is fed from a hopper, similar to the configuration of the screw system in injection molding. The screw forces the material through a tapered opening in the die. The heat and friction causes plasticizing to occur, softens the material, and forces it through the die opening. The material is cooled by either air or water. The rate of cooling can be controlled and further forming is possible. For example, pvc pipe is extruded as well as electrical conduit. If allow to be immersed in hot water, the conduit can be bent at 90 degree angles. Typical products that are extruded include tubing, rods, bars, moldings, sheets and films. Extrusion is also used for coating wire and cable.



Extrusion is a process for producing a continuous uniform product of constant cross-sectional shape. Typical products include pipe (1-1,500mm diameter), film, sheet, fibre, tape, rod, wire coating and profile such as curtain rail. The essential components of an extrusion line (Fig. 9-2) are the extruder, die, haul off and secondary shaping apparatus. Pellets or granules are fed into the hopper, from where they are drawn along the barrel and gradually melted. The molten polymer then flows through the die and is taken up by a haul-off device.

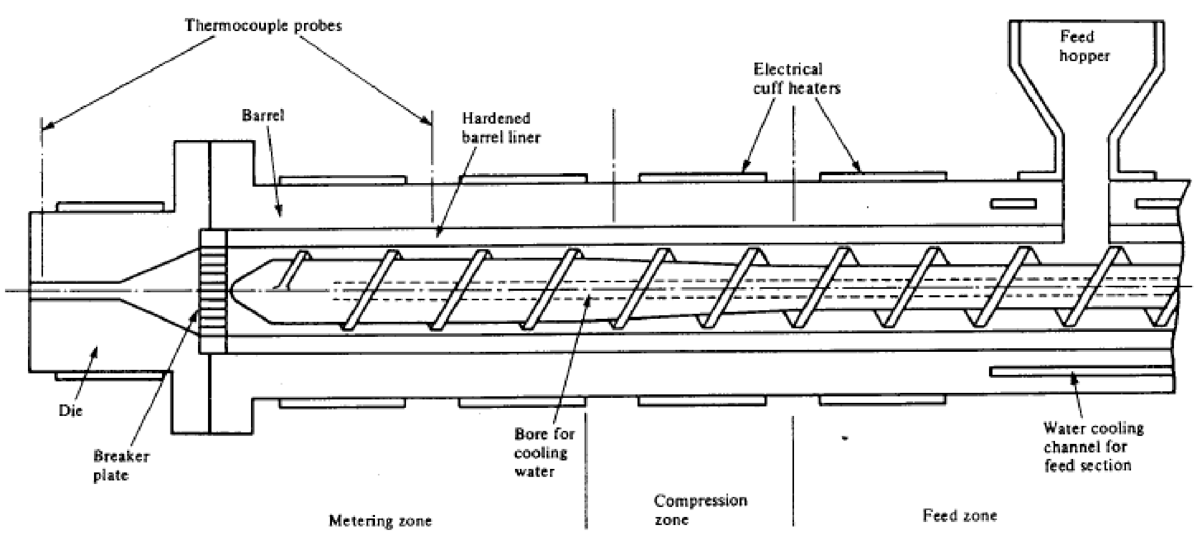


Figure 9-2: Features of a single screw extruder

Extruder

The aim of the extruder is to **melt** or plasticate the feed, ensure adequate **mixing** and act as a pump to **transport** a steady stream of polymer melt to the die. The extruder consists of one or two archimedean screws rotating in a close fitting barrel. This produces a helical channel of constant width. The depth varies along the length of the screw, from a large value at the feed end, through a uniform taper in the compression section, to a shallow uniform depth at the metering end.

The barrel can be externally heated by heater bands or cooled by water channels. Temperatures are in the range 200 – 300oC depending on material. Screw speeds are typically 50-150 rpm, whilst output rates range from 10-1,000 kg/hour.

Pressures of up to 40 MPa can be developed within the extruder. Temperature control is maintained by thermocouples along the barrel and pressure control by a transducer in the metering zone and a valve before the die.

The extruder screw will typically have a diameter of 25-150mm, with length/diameter ratio of 25-30. Usually the screw will consist of three regions:

Feed zone Has the function of preheating and supplying the correct quantity of material to the next zone. It is important to avoid overfeeding or starving this zone. Operation is influenced by shape and frictional properties of feedstock and screw geometry.

Compression zone Has the function of removing air (compaction) and melting the polymer. Melting is achieved by friction and conductive heating which is aided by reduction in material thickness.

Metering zone Has the function of producing a homogeneous melt (distributive mixing) and maintaining a constant temperature and pressure at the die.

Alternative screw configurations are sometimes used for different materials (see Fig. 9-3). Twin screw extruders may be required for some materials (eg PVC) to produce adequate mixing.

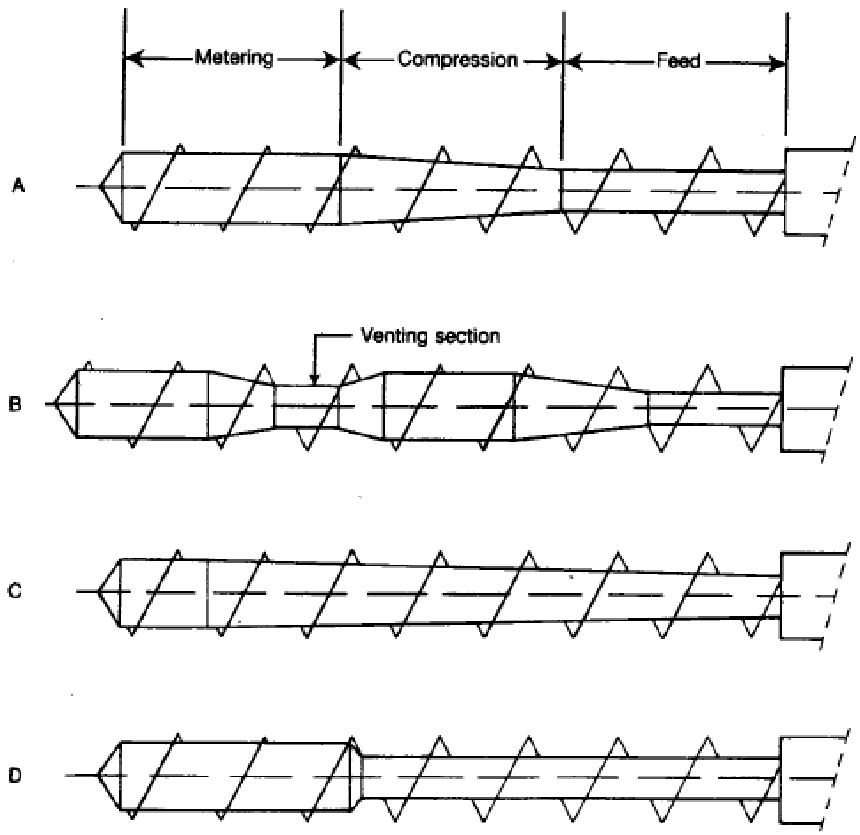


Figure 9-3: Four types of extruder screw: A – traditional, three zone screw; B – three zone screw with venting section; C – PVC type screw for amorphous polymers; D – Nylon type screw for crystalline polymers with a sharp melting point

Other important features of extruders include:

Venting Necessary to allow moisture to escape, which would otherwise affect the quality of output.

Filter A fine gauze to remove inhomogeneous material and any contaminations.

Breaker plate A plate with large holes which prevents dead spots, straightens the spiralling melt, and assists the build up of back pressure in order to improve mixing.

Extruder Die

The extruder die has the function of determining the desired shape of the extrudate (although subsequent shaping may be performed downstream). The die is externally heated and ensures that the flow channel changes shape smoothly from the barrel shape to the product shape. For example, for producing rod a conical taper is required whilst for producing a sheet a coat-hanger shaped die is required. The latter type also ensures constant melt velocity at the die exit. A typical die for producing pipe or tubing is shown in Fig. 9-4.

The main problem with a die is the **material swell** at the exit, which arises from the elastic properties of the melt. Together with draw down of the material, which is necessary for ensuring a straight product, the determination of final product dimensions is usually a trial and error process. In some cases a shaping plate or template is necessary to define the shape.

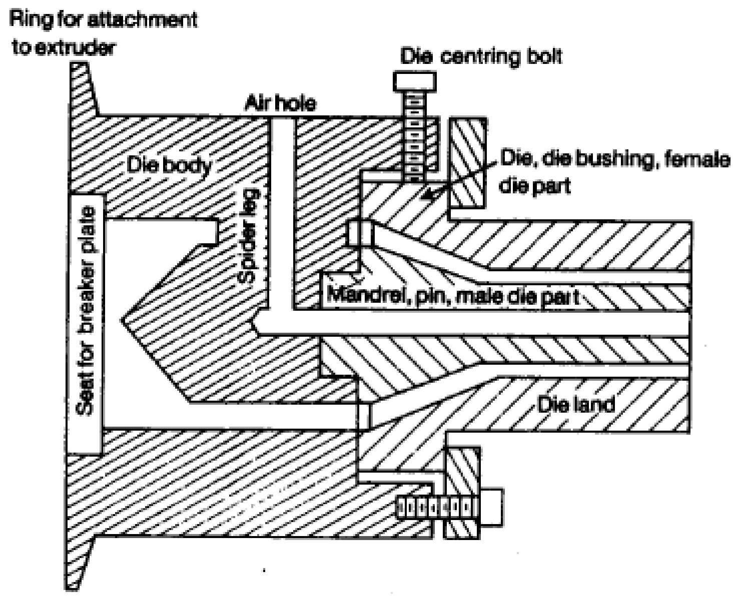
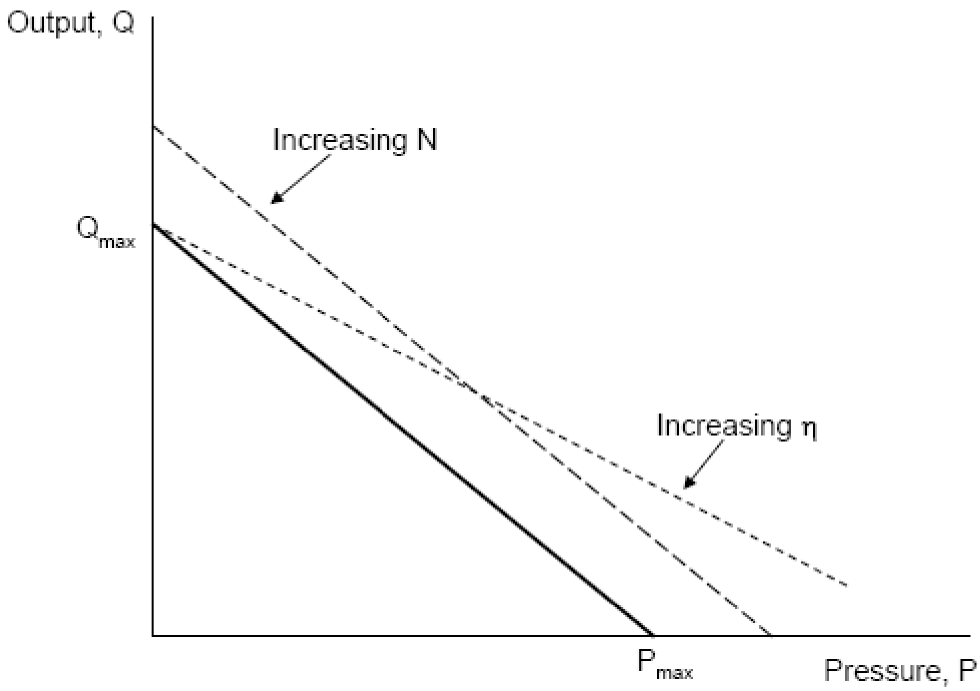
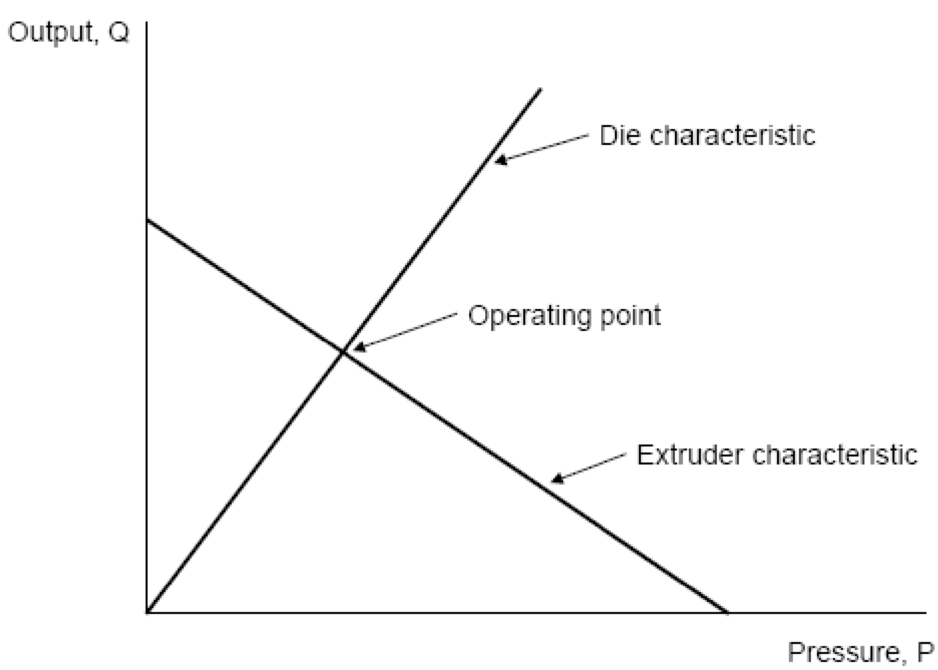


Figure 9-4: Pipe or tubing die

The output rate of an extruder die depends on the pressure drop across it. An increase in pressure gives an increased output. However, this pressure can act in a backward sense to reduce the transport of material through the metering zone. It is necessary, therefore, to match the screw and die designs to obtain an optimum output for a specific material. Cooling of the extrudate needs to be rapid to maintain shape and water baths are frequently used. From this aspect it is better to extrude at low temperature, although this would result in reduced production and the necessity for higher pressures.

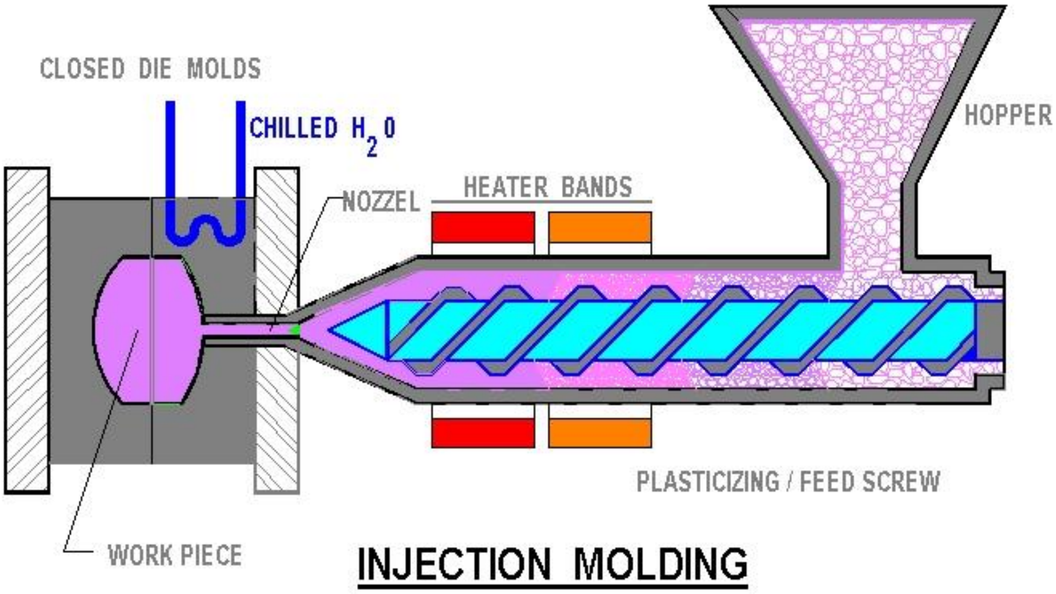
Extruder Characteristic Curves





Extruder and Die Characteristic Curves

Injection Molding Process



Injection molding is one of the most common processing methods for plastics Nowadays every home, every vehicle, every office, every factory contains a multitude of different types of articles which have been injection moulded. These include such things as electric drill casing, yoghurt cartons, television housings, combs, syringes, paint brush handles, crash helmets, gearwheels, typewriters, fascia panels, reflectors, telephones, brief cases – the list is ead1ess.

The original injection molding machines were based on the pressure die casting technique for metals. The first machine is reported to have been patented in the United States in 1872, specifically for use with Celluloid. This was an important invention but probably before its time because in the following years very few developments in injection molding processes were reported and it was not until the 1920s, in Germany, that a renewed interest was taken in the process. The first German machines were very simple pieces of equipment and relied totally on manual operation. Levers were used to clamp the mould and inject the melted plastic with the result that the pressures which could be attained were not very high. Subsequent improvements led to the use of pneumatic cylinders for clamping the injection which not only lifted some of the burden off the operator but also meant that higher pressures could be used.

The next major development in injection molding, i.e. the introduction of hydraulically operated machines, did not occur until the late 1930s when a wide range of thermoplastics started to become available. However, these machines still tended to be hybrids based on die casting technology and the design of injection molding machines for plastics was not taken really seriously until the 1950s when a new generation of equipment was developed. These machines catered more closely for the particular properties of polymer melts and modern machines are of the same basic design although of course the control systems are very much more sophisticated nowadays.

In principle, injection molding is a simple process. A thermoplastic, in the form of granules or powder, passes from a feed hopper into the barrel where it is heated so that it becomes soft. It is then forced through a nozzle into a relatively cold mould which is clamped tightly closed. When the plastic has had sufficient time to become solid the mould opens, the article is ejected and the cycle is repeated. The major advantages of the process include its versatility in molding a wide range of products, the ease with which automation can be introduced, the possibility of high production rates and the manufacture of articles with close tolerances. The basic injection molding concept can also be adapted for use with thermosetting materials.

Details of the Process

The earliest injection molding machines were of the plunger type as illustrated in Fig. 1 and there are still many of these machines in use today. A pre-determined quantity of molding material drops from the feed hopper into the barrel. The plunger then conveys the material along the barrel where it is heated by conduction from the external heaters. The material is thus plasticized under pressure so that it may be forced through the nozzle into the mould cavity. In order to split up the mass of material in the barrel and improve the heat transfer, a torpedo is fitted in the barrel as shown.

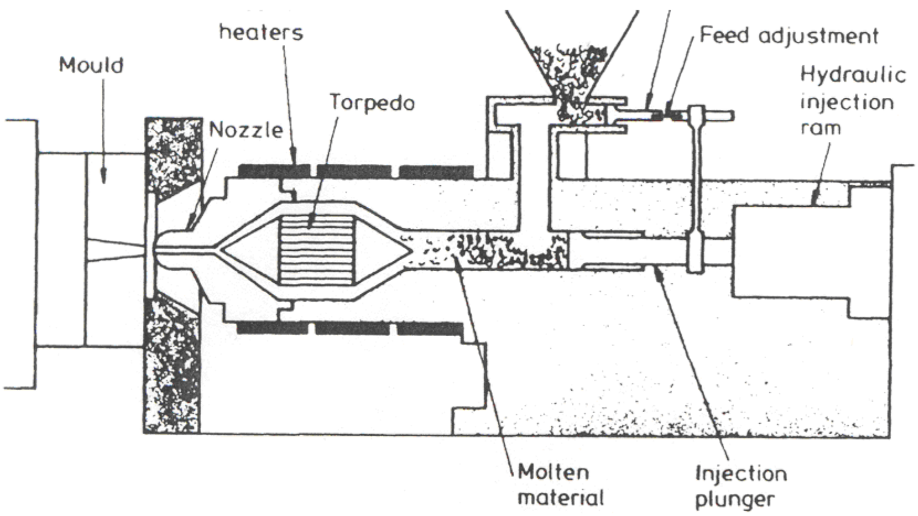


Fig 1. Plunger type injection machine

Unfortunately there are a number of inherent disadvantages with this type of machine which can make it difficult to produce consistent molding. The main problems are:

(a) There is little mixing or homogenization of the molten plastic.

(b) It is difficult to meter accurately the shot size. Since metering is on a volume basis, any variation in the density of the material will alter the shot weight.

(c) Since the plunger is compressing material which is in a variety of forms (Varying from a solid granule to a viscous melt) the pressure at the nozzle can vary quite considerably from cycle to cycle.

(d) The presence of the torpedo causes a significant pressure loss.

(e) The flow properties of the melt are pressure sensitive and since the pressure is erratic, this amplifies the variability in mould filling.

Some of the disadvantages of the plunger machine may be overcome by using a pre-plasticizing system. This type of machine has two barrels. Raw material is fed into the first barrel where an extruder screw or plunger plasticizes the material and feeds it through a non-return valve into the other barrel. A plunger in the second barrel then forces the melt through a nozzle and into the mould. In this system there is much better homogenization because the melt has to pass though the small opening connecting the two barrels. The shot size can also be metered more accurately since the volume of material fed to the second barrel can be controlled by a limit switch on its plunger. Another advantage is that there is no longer a need for the torpedo on the main injection cylinder.

However, nowadays this type of machine is seldom used because it is considerably more complicated and more expensive than necessary. One area of application where it is still in use is for large mouldings because a large volume of plastic can be plasticized prior to injection using the primary cylinder plunger.

For normal injection moulding, however, the market is now dominated by the reciprocating screw type of injection moulding machine. This was a major breakthrough in machine design and yet the principle is simple. An extruder type screw in a heated barrel performs a dual role. On the one hand it rotates in the normal way to transport, melt and pressurize the material in the barrel but it is also capable, whilst not rotating, of moving forward like a plunger to inject melt into the mould. A typical injection moulding machine cycle is illustrated in Fig. 2. It involves the following stages:

(a) After the mould closes, the screw (not rotating) pushes forward to inject melt into the cooled mould Fig. 2.a. The air inside the mould will be pushed out through small vents at the furthest extremities of the melt flow path.

(b) When the cavity is filled, the screw continues to push forward to apply a holding pressure (see Fig. 2.b). This has the effect of squeezing extra melt into the cavity to compensate for the shrinkage of the plastic as it cools. This holding pressure is only effective as long as the gate(s) remain open.

(c) Once the gate(s) freeze, no more melt can enter the mould and so the screw-back commences , Fig. 2.c. At this stage the screw starts to rotate and draw in new plastic from the hopper. This is conveyed to the front of the screw but as the mould cavity is filled with plastic, the effect is to push the screw backwards. This prepares the next shot by accumulating the desired amount of plastic in front of the screw. At a pre-set point in time, the screw stops rotating and the machine sits waiting for the solidification of the moulding and runner system to be completed.

(d) When the moulding has cooled to a temperature where it is solid enough to retain its shape, the mould opens and the moulding is ejected. The mould then closes and the cycle is repeated (see Fig. 3).

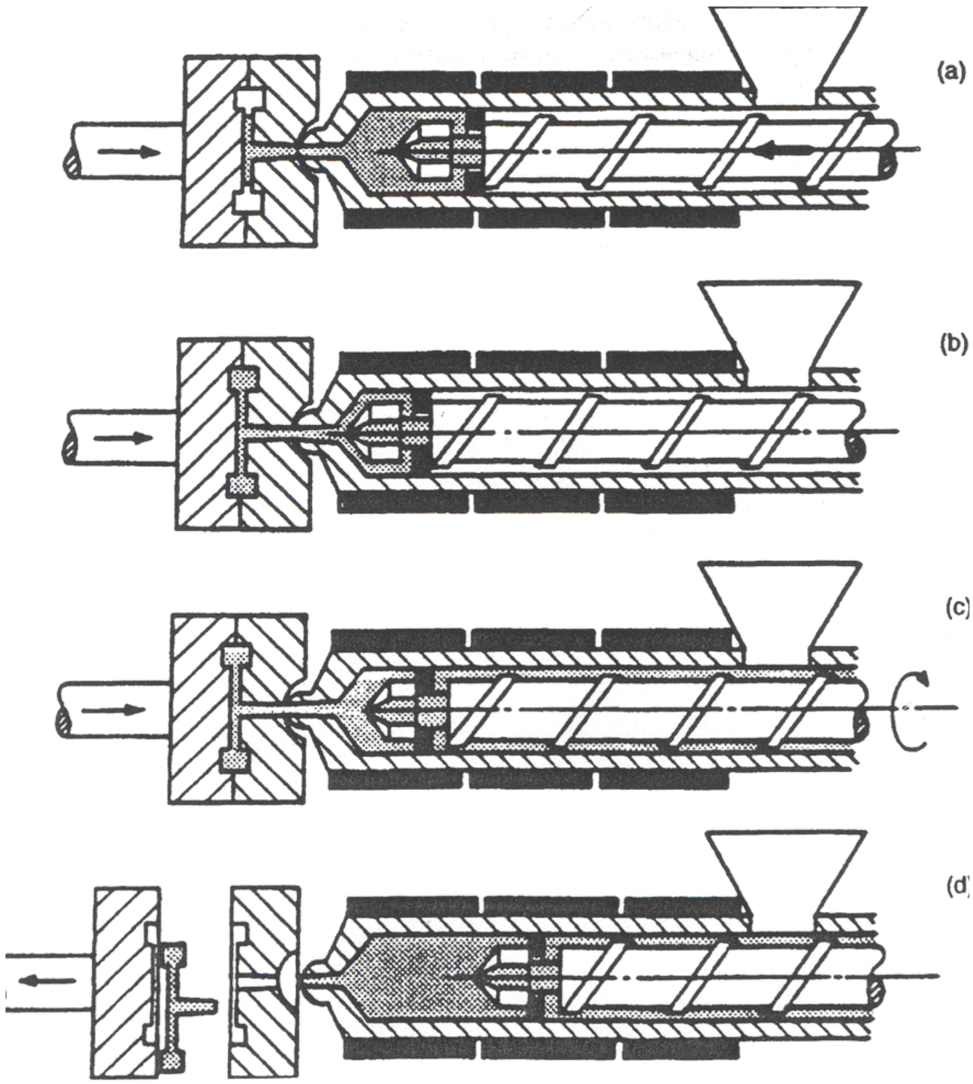


Fig. 2 Typical cycle in reciprocating screw injection moulding machine

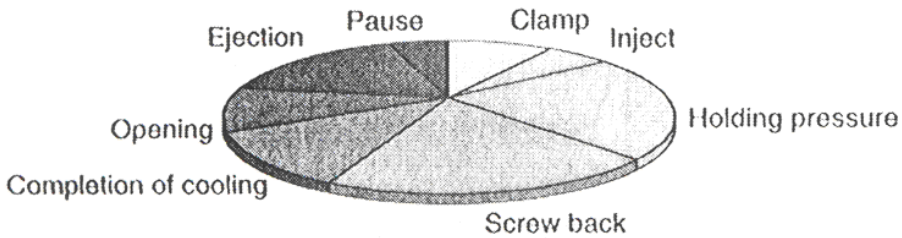
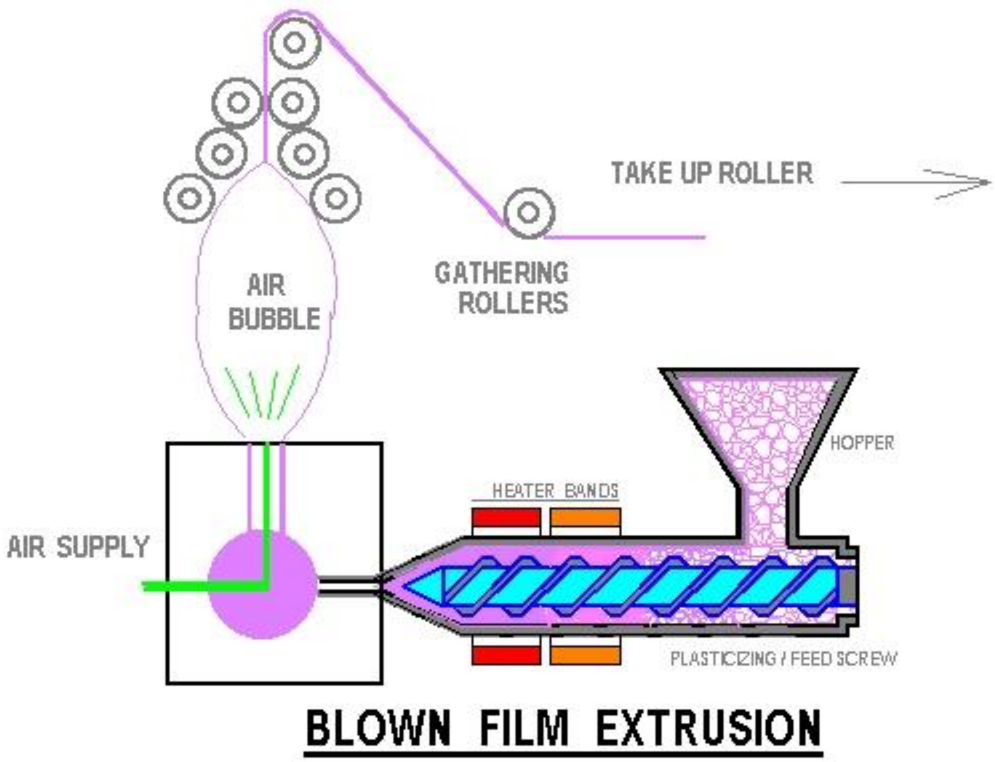


Fig.3 Stages during injection moulding

Blown Film Process



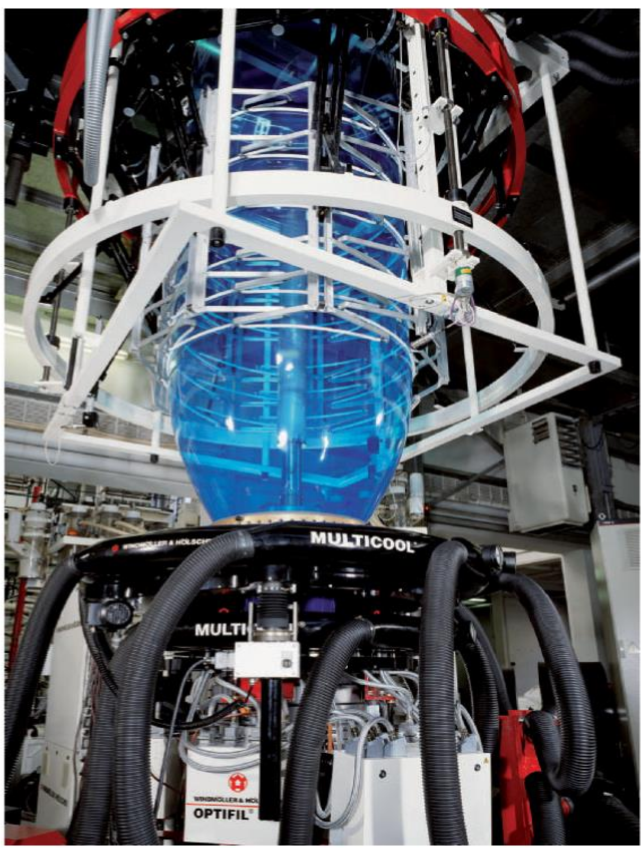
Blown film extrusion is one of the most significant polymer processing methods. Several billion pounds of polymer, mostly polyethylene, are processed annually by this technique. While some applications for blown film are quite complex, such as scientific balloons (Fig. 1), the majority of products manufactured on blown film equipment are used in commodity applications with low profit margins: grocery sacks, garbage bags, and flexible packaging (Fig. 2). Consequently sophisticated hardware, materials, and processing methods have been developed to yield film at very high output rates with both low dimensional variation and consistent solid-state properties.

Figure 1. A high altitude, scientific balloon being prepared for launch

Figure 2. Blown film extrusion is used to produce very high volumes of commodity products such as grocery and produce bags

Polymer chemistry and molecular structure are vital in establishing film properties, but bubble geometry resulting from processing conditions is also significant. Molecular orientation and crystalline structure – controlled by bubble dimensions – affect properties such as tensile strength, impact toughness, and clarity.

As a manufacturing process, blown film is somewhat unique, even compared with other extrusion processes. Molten polymer generally exits the die vertically in the form of a freely extruded bubble reaching heights of 50 feet (15 meters) or more (Fig. 3). Guides surrounding the bubble may limit its mobility, but it is still quite exposed to dimensional variation compared to the fixed extrudate in most other extrusion processes, which use vacuum sizers, calibrators, rollers, or other techniques. Depending on processing conditions, the blown film bubble has a shape freedom that allows almost any number of profiles within a designed range. Operators must have a relatively high skill level to accurately obtain the required bubble geometry (i.e., the shape resulting in specified product dimensions and properties).



The strong interdependence of process variables is another aspect of the process that requires a high level of operator skill and has led to extensive advancements in measurement and control techniques. There are many process variables – screw speed, nip speed, internal bubble air volume, and cooling rate (frost-line height) – that influence bubble geometry and, as a result, film properties. An adjustment to any one of these variables leads to a change in several geometric characteristics of the bubble. For example, an operator may intend only to decrease film thickness by increasing the nip speed; however, if no other control is modified this adjustment will also create an increase in both frost-line height and layflat width. Therefore, the proficient operator is aware of the influence of each process variable on all geometric characteristics of the bubble and can control more than one characteristic at a time.

Bubble Geometry

Although bubble geometry is not specifically hardware, it is included in this section because the hardware directly affects the bubble's geometry. The following paragraphs detail the geometric considerations of bubble shape.

The specific shape of the bubble (Fig. 3.8) depends on the combined influence of several process parameters. In general, the bubble usually has a small diameter and large thickness at the die exit and transitions to a large diameter and small thickness as it moves upward toward solidification. Above some point, the geometry is "frozen-in" and remains virtually constant.

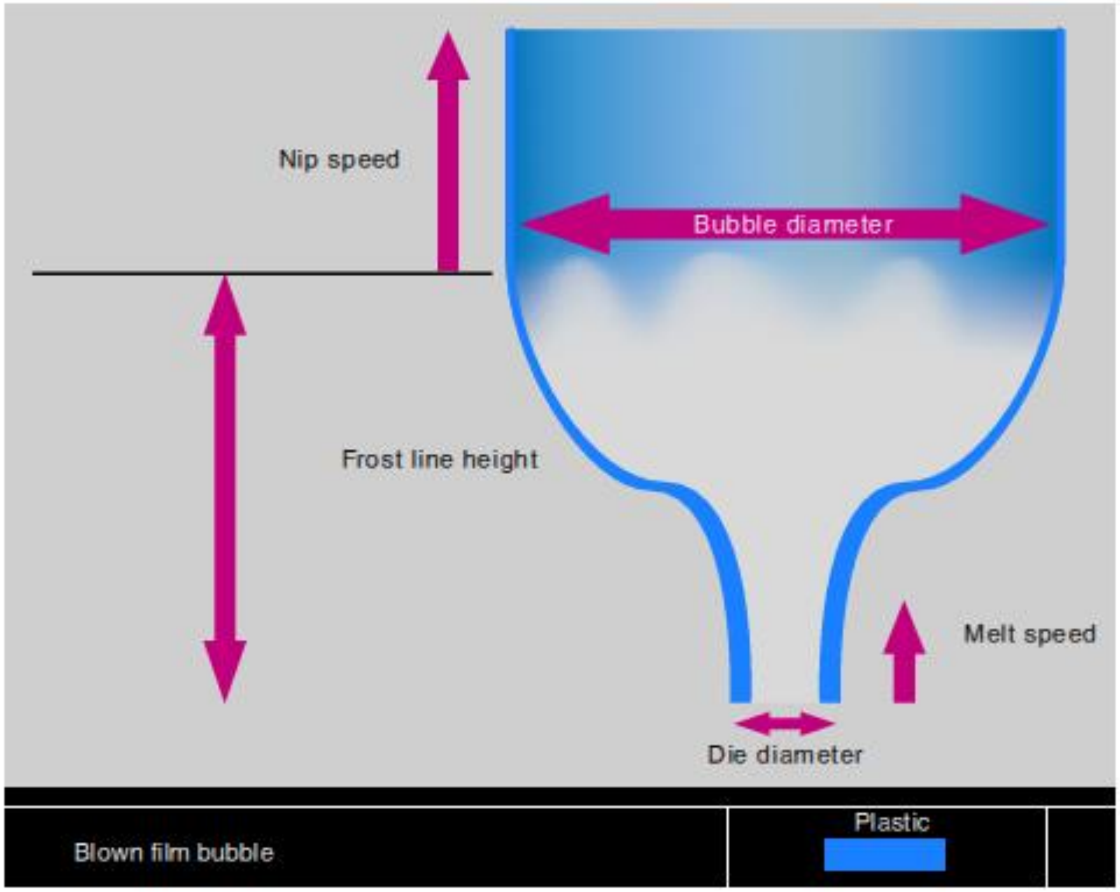


Figure 4. Bubble geometry characteristics

There are several parameters used to describe the geometry of the bubble:

- Die diameter
- Die gap
- Frost-line height
- Stalk
- Bubble diameter (BD)
- Film thickness
- Layflat width (LF)

The die diameter represents the initial bubble diameter as it leaves the die, and the die face in the molten state, it is cooled and eventually reaches a temperature where it becomes a solid. The distance from the die face to where this solidification takes place is called the frost-line height. The name is derived from operations where it appears that the film is optically frosting as it becomes cloudy due to polymer crystallization. Conventionally, the frost line is defined as the lowest point where the bubble is at its maximum diameter because there is effectively no further stretching above this point. The bubble region below the frost line is known as the stalk or neck, particularly when it is relatively long. Above the frost line, where geometry is effectively frozen-in, the terms bubble diameter and film thickness are simply used for those characteristics. Once the film is collapsed flat and passes through the nip rollers, the two layer web is characterized by a layflat width. Twice the layfl at width is equivalent to the circumference of the bubble (or BD = 2 LF/ð). In many cases, it is easiest to measure the layflat width, so this equation becomes a handy tool for determining the bubble diameter.

Several process variables work together to determine the bubble geometry:

- Melt speed
- Nip speed
- Internal bubble volume
- Cooling rate

The melt speed is the upward velocity of the polymer as it exits the die gap. It is controlled by the screw speed, but it is not the same as the screw speed (for one thing, the melt speed is linear and the screw speed is rotational). The nip speed (also called film speed, line speed, and take-off speed) is the velocity of the polymer as it travels through the nip rollers. The film travels essentially at the nip speed at all points above the frost line. In all cases, the film increases in velocity from the die face, where it travels at the melt speed, to the frost line, where it travels at the nip speed. This acceleration leads to thinning of the melt curtain to obtain a thin film. The internal bubble volume is the amount of air contained inside the bubble between the die face and the nip rollers. A similar variable that can be used alternatively is the internal bubble pressure. The cooling rate is determined by the speed at which the cooling air impinges on the bubble and the temperature of that air. There are several other process variables that infl uence bubble geometry, such as process temperatures, die design, feed material composition, and polymer flow properties, but these generally remain constant for a given run.

A distinction is often made between two general types of bubble shapes (Fig. 5) that are selected by the processor for a given resin type. The pocket bubble has little or no stalk, beginning its expansion almost immediately above the die face.

This shape is mostly used for low-density polyethylene, linear low-density polyethylene, and polypropylene. The pocket bubble tends to be quite stable due to the cooling air providing early solidification.

The other shape is the high (or long) stalk bubble. This type is used primarily for high- density polyethylene due to that material's relatively low melt strength. In this process, TD stretching is delayed until the polymer reaches a lower temperature, allowing for a more stable melt and providing higher stress during TD stretching.

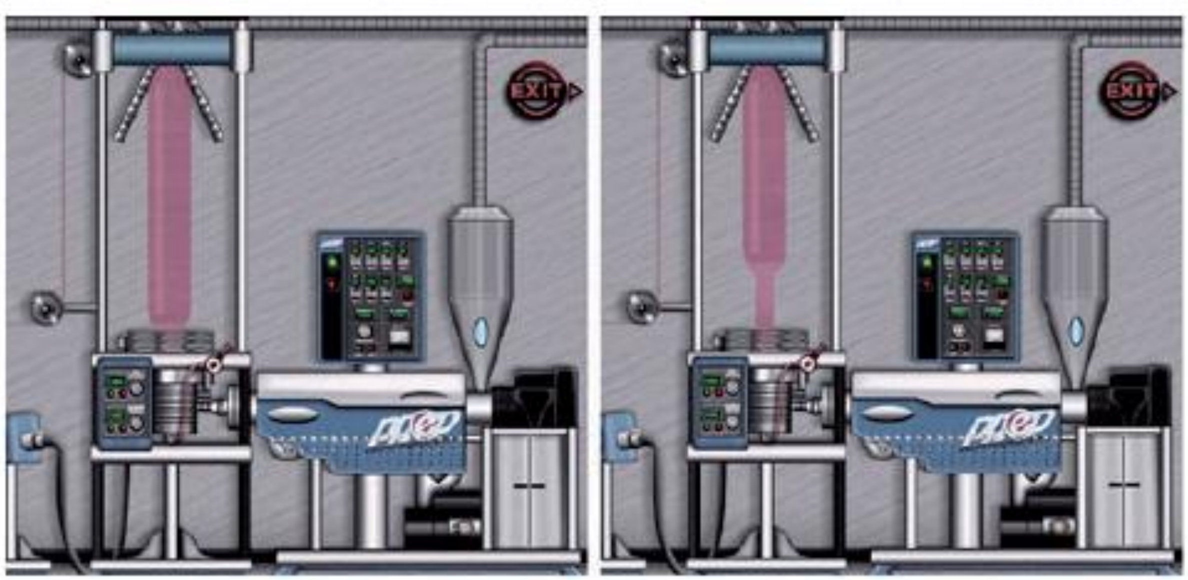


Figure 5. Pocket bubble on left and high (long) stalk bubble on right

Bubble Cooling

Bubble cooling is generally accomplished by blowing a large volume of air on the film as it exits the die (Fig. 6). This may take place on only the outside of the bubble or on both the inside and the outside. Additionally, the bubble is kept inflated to remove more heat from the film as it travels up through ambient air in the cooling tower.

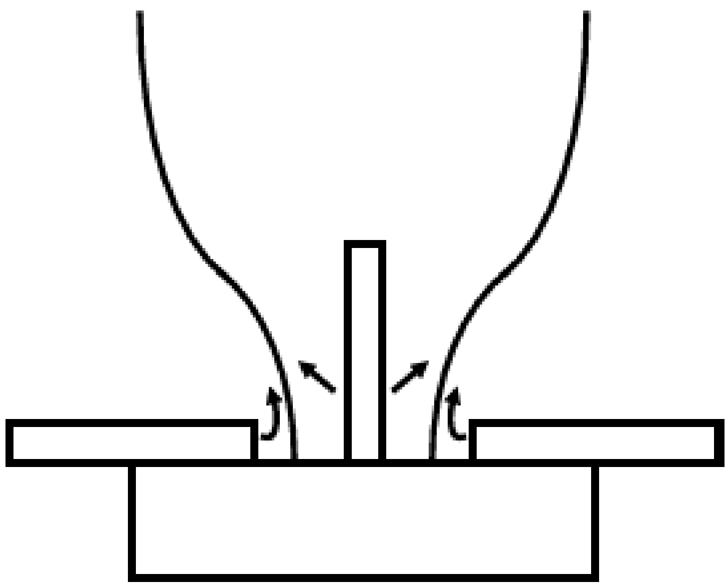


Figure 6. Bubble with external cooling and internal cooling

Bubble cooling deserves much attention. In many blown film operations, it is the limiting factor to maximizing throughput. Therefore, it is important to have a thorough understanding of the variables that influence the removal of heat from the bubble and ways to improve the efficiency of this process.

Polyethylene materials tend to retain heat more than most other polymers. A measure of this tendency is the specific heat value. Polyethylene grades have a specific heat in the range of 1.8–2.3 kJ/kg·°C. Most other polymers have a specifi c heat in the range of 0.9–1.5 kJ/kg·°C. For this reason, high cooling towers are necessary to remove enough heat in the film that the two sides will not adhere together while passing through the nip rollers.

Three primary process variables are responsible for the efficiency of cooling: air speed, air temperature, and air humidity. Air speed is generally measured as a volumetric flow, such as cubic feet per minute. At higher air speed, more heat is removed from the film per unit time.

Air speed is determined by the capability of the blower unit and by the static pressure at the blower outlet (Fig. 7). As static pressure is increased, the blower becomes less efficient, delivering fewer cubic feet per minute at a given motor speed.

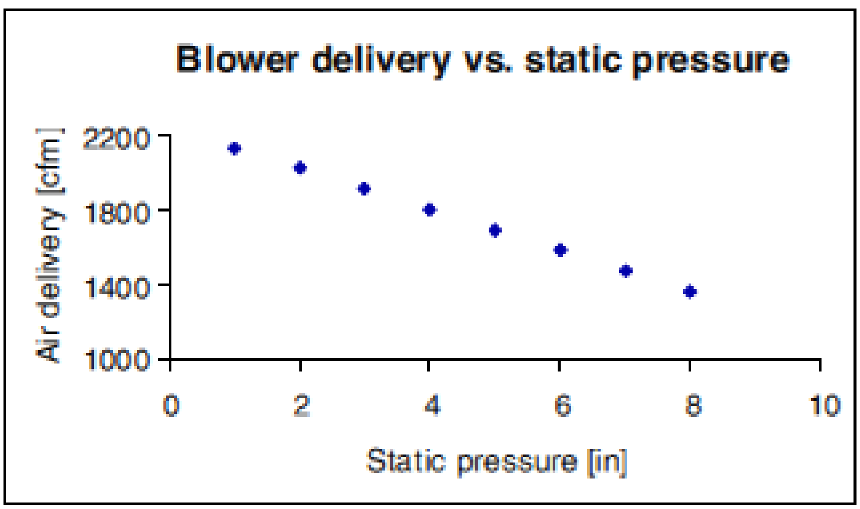


Figure 7. As the static pressure on the blower is increased, the blower efficiency decreases

Factors that affect static pressure are the number, length, and diameter of cooling hoses and flow restrictions within the hoses or air ring.

Another variable affecting cooling efficiency is the temperature of the air impinging on the bubble. Cooler air will remove heat more quickly, but using chilled air increases processing costs so a balance must be reached. As a side note, if a chiller is used to cool the air, it is good practice to insulate cooling hoses, manifolds, and air rings because this will minimize moisture condensation.

Ambient air temperature around the extrusion line also has a large effect on bubble cooling, even when chilled air is used in the process. This is why frost-line height may change significantly from day shift to night shift in plants that are not air-conditioned.

A third cooling variable is air humidity. If a chiller is used, then the air impinging on the bubble is typically quite dry. However, if ambient air is used, the humidity will vary seasonally and may affect cooling efficiency. Most plant personnel report that cooling efficiency goes down when the air humidity is higher. However, humidity is generally higher at the same time that air temperature is higher, so separating the effects simply by observation is difficult. The physics indicate that more humid air would actually be more efficient at cooling the bubble, so further research is needed in this area.

The principal hardware component responsible for cooling is the air ring. This device is located just on top of the die with a layer of insulating material (or air) between it and the hot die face (Fig. 8). The air ring surrounds the bubble and delivers cooling air directly onto the bubble. It receives air from the blower through, typically, a number of hoses that attach around the circumference of the device. Inside the air ring, a series of baffled flow channels distribute the air in such a way as to produce a uniform airflow (volume and velocity) at all points around the circumference of the bubble.

The importance of the insulator between the air ring and the die is often underestimated. A missing, damaged, or poorly chosen insulator will allow the die to transfer a large amount of heat through the air ring and into the cooling air. This results in decreased production efficiency. Additionally, an air ring sitting directly on the die face will draw heat out of the die, making uniform temperature control of the die difficult.

Figure 8. A blown film air ring.

Line Control

The goal of line control is to maintain minimum variation in all measurable film quantities with respect to both position and time. In other words, minimal variation is desired in a measurement such as film thickness from one position on the bubble to another and, at a given position, from one time to another. The high interdependence of process variables on film quality makes this an ambitious objective.

Sophisticated control systems have been developed in response to the high interdependence of several process variables coupled with the demands of very high output rates. While many lines still utilize primarily manual controls, a growing number of blown film systems depend on computer-based measurement and control of all key process variables. These computer-based systems can make an important contribution to increasing efficiency, reducing costs, and increasing profits on high output lines.

This section explains how film dimensional and property consistency results from maintaining process uniformity in four key areas:

- Melt from the extruder (or melt quality)
- Film thickness (or gauge)
- Layflat width (or, alternatively, bubble diameter)
- Frost-line height

The following paragraphs focus on achieving uniformity in each of these four areas.

Providing high melt quality to the die is the primary objective of the extruder. High melt quality can be defined as homogeneous material of constant temperature and pressure. Homogeneity of the melt depends on several factors, such as the uniformity of the raw material, adequate melting capability of the screw, and adequate mixing capability of the screw and/or static mixer. Raw materials are often sampled in-house or at an outside testing facility to ensure minimal lot-to-lot variation. Variations in the composition ratio of solids (the ratio of first-generation, reprocessed, fluff material, and additives) entering the extruder can lead to nonuniformities in the melt, so should be minimized as an objective of the feed system. Finally, screw design is the critical element in making certain the melting of solids along the barrel proceeds stably and the melt leaves the extruder adequately mixed.

To maintain a constant melt temperature, we must consider potential variations with respect to both position and time. Position variations refer to temperature differences between, for example, the wall surface of a melt stream and the internal core. If melt with a large temperature distribution enters the die, it can result in different temperature streams flowing to different positions around the die exit. This leads to gauge variations. Methods to reduce these variations include screw mixing elements, static mixers after the extruder, and flow channel design within the die. Time-dependent temperature variations (large swings from high to low) must be minimized by the extruder temperature control system. Additionally, screw speed stability and feed material consistency is crucial for good temperature control.

Constant melt pressure is the final requirement for high melt quality. The pressure of the melt entering the die, or head pressure, is determined by three variables: head/die flow channel geometry, polymer flow rate, and polymer viscosity. In general, the hardware geometry remains fixed so pressure fluctuations are caused by any changes in flow rate or viscosity as described in the next two paragraphs. However, one change related to hardware geometry, or more specifically flow restriction, is the buildup in front of filtering screens. Monitoring this buildup of contamination is important because of its effects on increasing head pressure which impacts safety and process efficiency.

Polymer flow rate is kept constant when the screw processes occur stably. That is, the stability of solids conveying, melting, mixing, and melt pumping is necessary to maintain a uniform flow rate through the die. It is not uncommon, particularly with significant amounts of reprocessed feed material, for solid conveying characteristics to change throughout a run, leading to detrimental pressure fluctuations.

Polymer viscosity variations may be caused by changes in either the raw material or the feed composition. Additionally, we can see viscosity changes when there are variations in hardware temperature, such as may occur with an unstable temperature control circuit.

The next process variable to be controlled is film thickness (gauge). Either on-line or off-line measurements allow us to monitor film gauge. On-line devices usually employ a radiation source, such as a gamma backscatter system. These devices measure thickness by emitting radiation that refl ects back to the sensor from both the near and far surfaces of the film. They can be mounted to measure a fixed location on the bubble or on a carriage to traverse around the bubble (Fig. 9). Also, a unit traversing back and forth across the flattened web can be used, but this measures two-layer thickness. Off-line devices typically operate on a capacitance principle, so they don't require the safety practices employed with radiation sources.

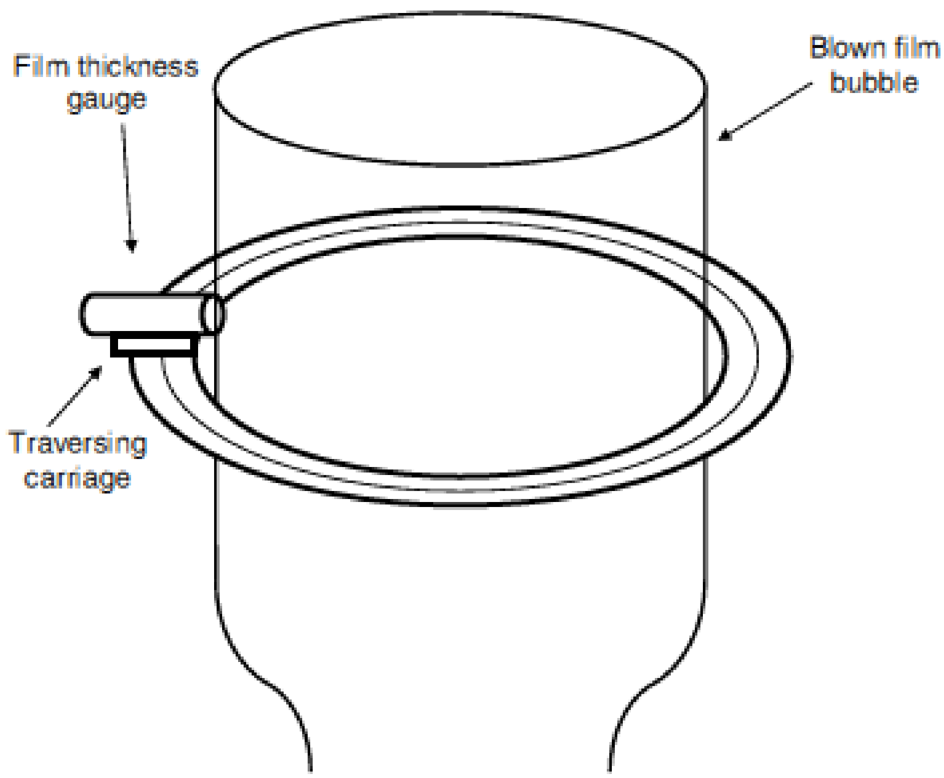


Figure 9. A thickness gauge mounted on a carriage to rotate it around the bubble

Several methods are used to adjust thickness. The best practice is to begin with a good die setup. Before each new run, the operator should check to make sure the die ring is centered on the pin. Although adjustments will almost always be necessary after start-up, this provides a good starting place for the extrusion run. Final adjustments are made by observing the shape of the bubble and monitoring film thicknesses. Once any asymmetry in the bubble is observed, the die bolts should be slightly tightened or loosened to move the ring around the pin so that a uniform thickness distribution results.

Adjustment of the die gap is an easily misunderstood concept. In some operations it is ignored, resulting in an ongoing attempt to compensate for uneven melt flow by other methods such as air ring adjustments. In other operations, personnel without the experience to appreciate the sensitivity of the process to these corrections perform the adjustment improperly. To make matters worse, blown film dies may be constructed such that tightening a die bolt increases the local die gap or such that tightening a die bolt decreases the local gap, creating confusion for line operators. In summary, it is good practice to make certain that key personnel responsible for process control are well trained on how to adjust specifi c dies and what conditions warrant a die adjustment. Sometimes, it is best to use other methods to create a symmetrical bubble, such as ensuring uniform die temperature around the die gap.

High output lines often employ automatic gauge control. One type of system utilizes a series of small heaters located around the circumference of the die lips. A downstream thickness measurement is reported back through a controller that decides whether to increase or decrease heat to a certain die lip zone, thus promoting or restricting flow to that zone. Other types of systems provide small air jets to several locations around the base of the bubble or selectively heat sections of the cooling air stream around the bubble. In these cases, a signal for increased or decreased airflow or temperature leads to a change in stretching of the melt.

Layflat width or, alternatively, bubble diameter is another process control variable. Layflat width can be measured manually with a tape measure but is most often measured automatically using a laser micrometer across the web (Fig. 10). Bubble diameter is measured by using ultrasonic sensors mounted on bubble guides or irises or by taking video of the film during a run and measuring the diameter from the video. Adjusting the internal bubble volume (or pressure) changes the bubble diameter (or layflat width). IBC systems can perform this automatically, or it can be done manually by opening a valve to allow more air into the bubble to increase the diameter or by making a cut in the bubble to release some of the air, thereby decreasing the diameter.

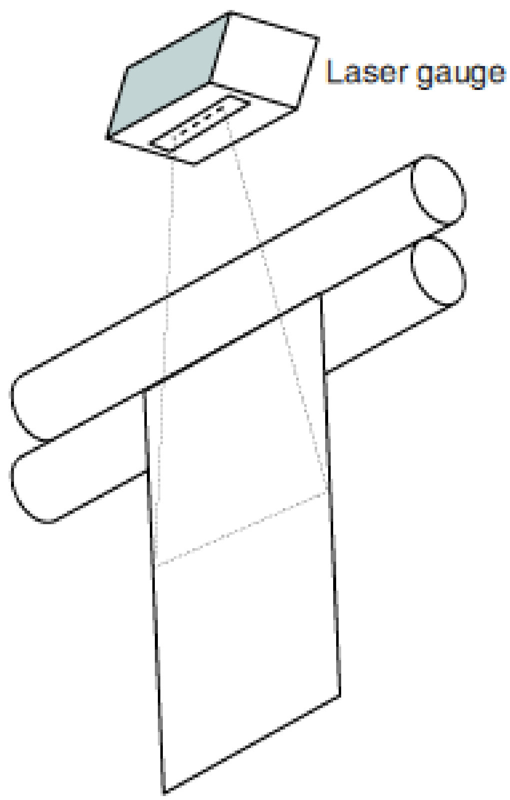


Figure 10. A laser gauge is used to measure layflat width

The final control variable is frost-line height. The position of the frost line is very sensitive to any changes in the process. Therefore, this is an excellent parameter to track as a measure of stability during a run. Any changes in ambient or process temperatures, line or screw speed, or material feed conditions will affect the frost-line height. This, of course, will lead to variations in film gauge and layflat as well.

When frost-line height is measured, it is done manually with a tape measure, electronically through an optical scan of the neck height, or by using infrared temperature measurement (Fig. 11). To control frost-line height, we can vary the blower motor speed or the temperature of the cooling air passing through the air ring. Again, this can be performed in a closed-loop or a manual mode.

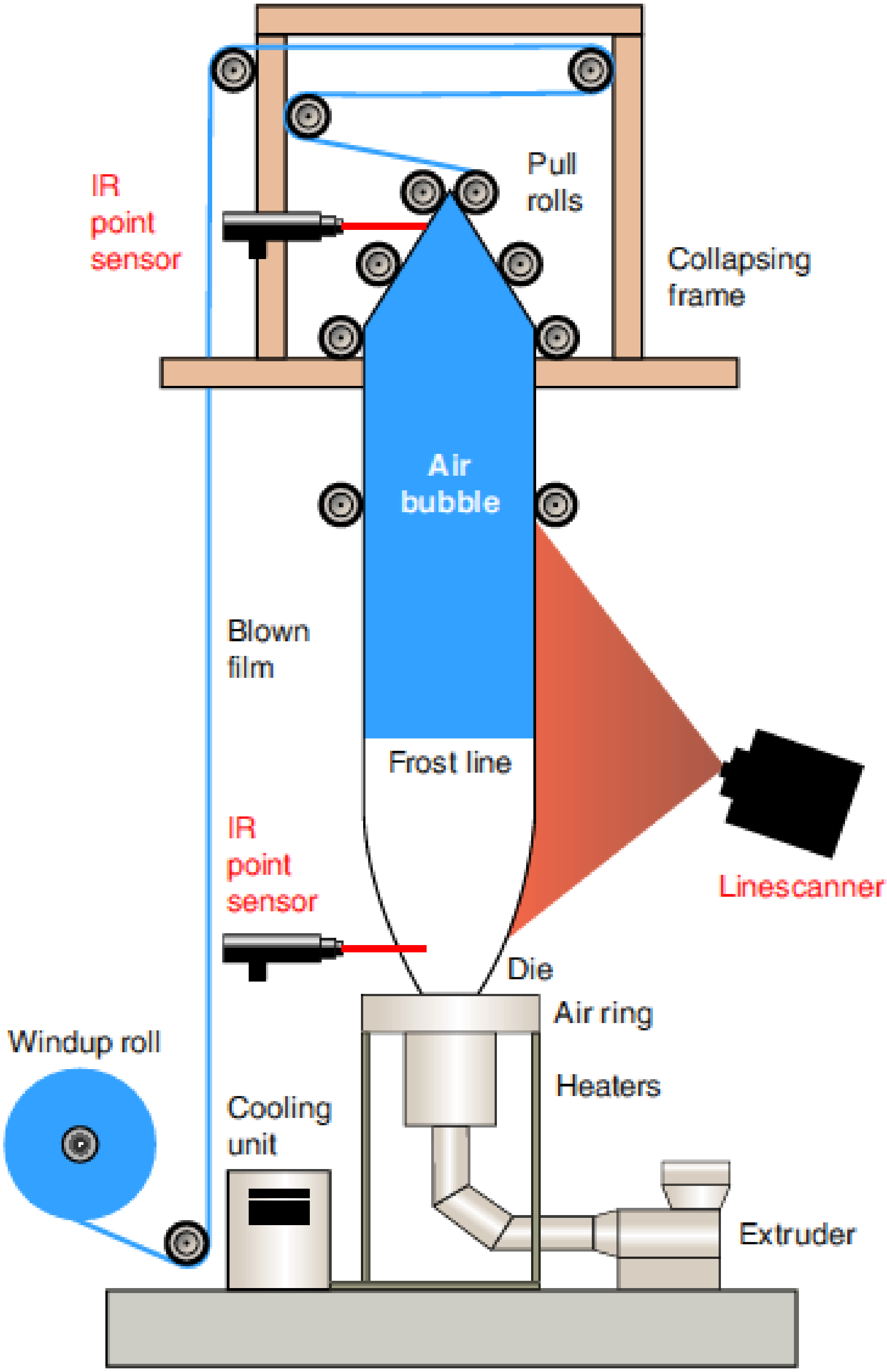


Figure 11. Online infrared temperature measurement system .