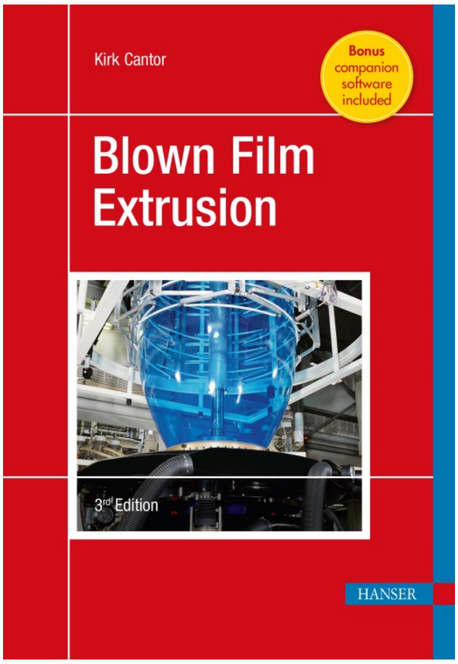
HANSER



Sample Pages

Blown Film Extrusion

Kirk Cantor

ISBN (Book): 978-1-56990-696-5
ISBN (E-Book): 978-1-56990-697-2

For further information and order see

www.hanserpublications.com (in the Americas)

www.hanser-fachbuch.de (outside the Americas)

Preface

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 (Figure 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 (Figure 2). Consequently, sophisticated hardware, materials, and processing methods have been developed to yield film at very high output rates exhibiting both low dimensional variation and consistent solid-state properties.

Figure 1 A high altitude, scientific balloon being prepared for launch *(National Aeronautics and Space Administration)*

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 (Figure 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 to only 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.

Figure 3 A blown film extrusion line *(Windmoeller & Hoelscher)*

From hardware and materials through processing and properties, this book is intended to provide the reader with a comprehensive understanding of blown film extrusion through a useful balance of theory and practice. Included in this book are the answers to why effects occur the way that they do in the blown film process, so the reader can improve his/her ability to troubleshoot and improve systems. At the same time, current practices and equipment are emphasized to keep readers up-to-date with the most productive and efficient technology.

The companion computer-based learning tool, *The Blown Film Extrusion Simulator*[1], enhances the reader's understanding. This software was developed specifically to teach blown film extrusion equipment operation and processing principles. The realistic graphic interface and intuitive operating techniques were designed to emulate actual processing methods, so learners can quickly move from the simulator to real production equipment. Throughout this book there are exercises (identified with the symbol) using the simulator to complement the methods and principles explained. It is intended that, when convenient, readers will take a break from reading the book and spend a few minutes with the simulator to enhance their understanding of the content. Before continuing to the next chapter, the reader may want to skip to Appendix 1 in Chapter 9 to learn how to download, install, and operate the simulator.

1 Available for download, together with the eBook Bonus, using your personal code at www.hanserpublications.com/ebookbonus.

Contents

3 Extrusion Overview

The extruder is the heart of all extrusion processes, continuously heating and mixing the feed material as it supplies a homogeneous melt to the die for shaping. Although the emphasis of this book is on the hardware and methods specific to blown film extrusion, this chapter provides a general overview of the extruder and its functions. Final product quality and production efficiency are highly dependent on the operation of the extruder.

This chapter covers two main sections: extruder hardware systems and extrusion functional zones. The first section identifies the primary components of the extruder and provides detail regarding their capabilities and size ranges. The second section describes how the hardware interacts with the material as it passes through the system. In other words, it provides a look at what is happening inside each zone of the extruder. The descriptions here are purposefully brief, serving as a foundation to support later discussions specific to blown film extrusion. If the reader is interested in pursuing this topic further, there are many books devoted entirely to the extruder and extrusion processes. For example, *Polymer Extrusion* by Rauwendaal [15] provides an excellent in-depth analysis. Other references are listed in the final section of this book [16–19].

3.1 Extruder Hardware Systems

The purpose of the extruder is to feed a die with a homogeneous material stream at constant temperature and pressure. This definition highlights three primary responsibilities that the extruder must accomplish while delivering material to a shaping die. First, it must homogenize, or satisfactorily mix, the material. Second, the material entering the die must have minimal temperature variation with respect to both time and position within the melt stream. Third, there must be minimal melt pressure variation with time. It is important that the design and operation of an extrusion system consider all three of these objectives to produce a quality product.

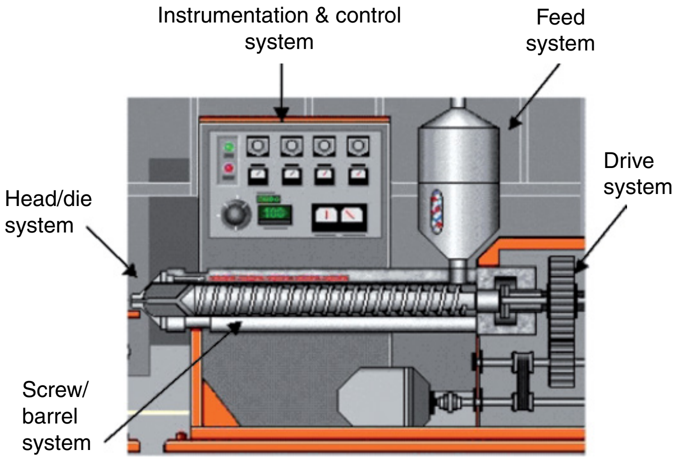


Figure 3.1 The five extruder hardware systems

Extruders are generally rated by screw diameter. Typical production extruders range in size from 2 to 6 in (50 to 150 mm). A fundamental quantity determined by screw diameter is the maximum throughput measured in pounds/hour or kilograms/hour. The relationship between throughput and screw diameter is cubic, dependent upon the volume inside the extruder available for the polymer. With a certain polymer, a 2-inch extruder may have a maximum throughput of 100 lb/h, while a 4-inch extruder would have a maximum throughput of 800 lb/h. Therefore, system requirements such as material handling capacity, motor size, cooling capability, and floor space increase rapidly with an increase in screw size.

Components of the extruder hardware can be categorized into five systems (Figure 3.1):

- Drive system
- Feed system
- Screw/barrel system
- Head/die system
- Instrumentation and control system

Simulator Exercise: When the cursor is paused over any extruder component, an identification tag shows the name of that component.

3.1.1 Drive System

The drive system supplies the mechanical energy to the polymeric material by rotating the screw. This system consists of a motor, a speed reducer, and a thrust bearing.

3.1.1.1 Motor

The motor is the source of power to turn the screw. Extruder motors tend to be relatively large due to the high power consumption by the polymer around the screw. Three sources of power consumption are 1) melting of solids via frictional heat generation, 2) conveying of high-viscosity molten polymer along the barrel, and 3) pumping of high-viscosity molten polymer through the die restriction. A rule of thumb for motor size is:

$$\text{Motor power (hp)} \cong \text{Throughput (lb/h)} \div 5$$

Extruder motors are usually electric, but some systems utilize hydraulic motors. For example, on injection and blow molding machines that use hydraulics to develop clamp tonnage, the extruder is also generally hydraulic. Electric motors are designed for either direct current (DC) or alternating current (AC). Traditionally, DC motors, which regulate speed through voltage control, have been more popular because they could provide the necessary power at a lower cost. However, recent advances in frequency control – the technique used to regulate speed in AC motors – have caused this type of motor to become more widely used.

3.1.1.2 Speed Reducer

Electric motors generally operate most efficiently at high rotational speeds. A typical maximum speed for an extruder motor is 2,000 rpm. However, extruders for blown film are usually designed to operate at much lower screw speeds. Therefore, the high motor speed is geared down to a lower screw speed with the help of a *speed reducer*, also known as a *gear box*.

Gear boxes usually have reduction ratios in the range of 10 : 1 to 20 : 1, resulting in typical maximum screw speeds of 100 to 200 rpm. Besides speed reduction, the gear box provides an additional advantage of increased torque. This would be analogous to providing rotational leverage. Because of the high power consumption of polymeric materials, high torque is needed to maintain screw speed. Most drive systems are designed to keep screw speed constant even if the torque requirement changes, which could be created, for instance, by a change in material viscosity.

Figure 4.20 A dual-station turret winder (*Windmoeller & Hoelscher*)

4.11 Film Treatment

Polyolefins, such as polyethylene and polypropylene, are non-polar polymers. This means that any polar materials will not easily wet the surface of (adhere to) these polymers. One area where this has important implications is in the printing conversion process. Inks cannot be absorbed into most films because they are typically nonporous. The only way the ink will stay on the surface of the film is if it wets the polymer rather than puddle up. To promote the ink adhering to the surface, it becomes necessary to treat the film to make it more polar.

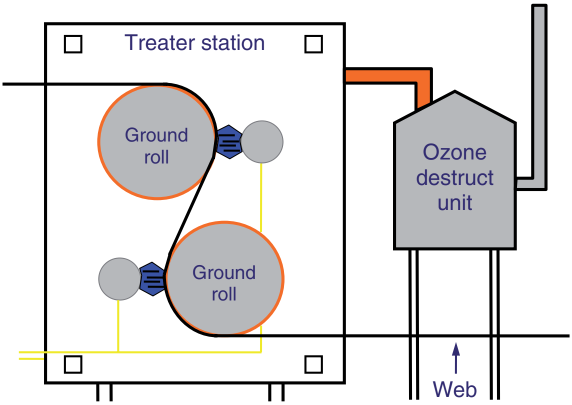


Figure 4.21 Corona discharge unit for treating (oxidizing) film surfaces (*Pillar Technologies*)

The most popular treatment process for blown film is the corona discharge method. Corona discharge units (Figure 4.21) are high-voltage devices that ionize the air in a small region through which the film travels. The ionization creates ozone, a very strong oxidizing chemical. The result is that the film is oxidized, creating a polar surface rich with oxygen atoms [32]. The level of oxidation needed for a given film may depend to some extent on the additive package in the raw material. Also, this type of surface treatment is not permanent. In most cases, the film must be printed within a few days of treatment because additives in the plastic may migrate (bloom) to the surface and inhibit the treatment.

Safety is a top concern where these high-voltage corona discharge systems are employed. Adequate venting is necessary in the vicinity of the corona to extract the ozone created by the discharge unit. Also, a shut-off interlock should be used in the event of a film line break.

4.12 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 [33]. While many lines still utilize primarily manual controls, a majority 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 homogenous 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 non-uniformities in the melt, and therefore should be minimized as an objective of the feed system. Finally, screw design is the critical element in ensuring that stable melting of solids occurs along the barrel and that 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 are 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, therefore 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 as long as the screw processes are stable. 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.

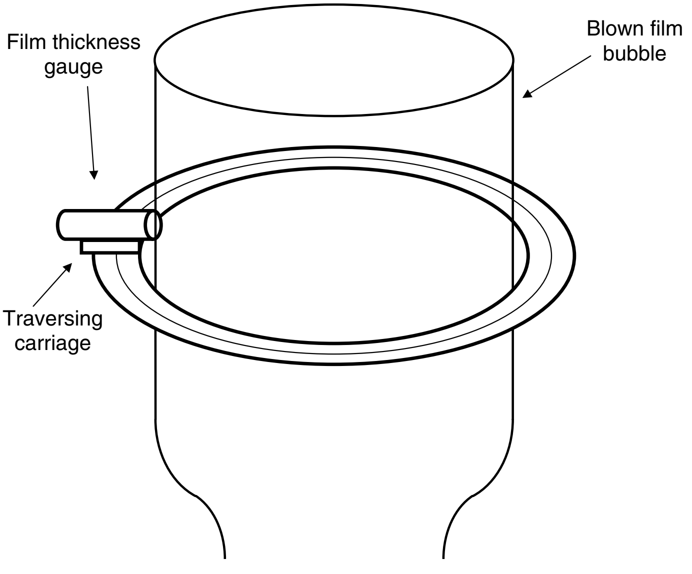


Figure 4.22 A thickness gauge mounted on a carriage to rotate it around the bubble

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 reflects 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 (Figure 4.22). Also, a unit traversing back and forth across the flattened web can be used, but this measures two-layer thickness. One measurement unit uses software to separate the contributions from each layer in combination with an infrared sensor that is capable of distinguishing between the individual thicknesses in multilayer film

5.1 Process Variables vs. Bubble Geometry

Table 5.1 defines the response that increasing either of the four main process variables (nip speed, screw speed, cooling speed, and bubble volume) has on each of the three main bubble geometric variables (film thickness, bubble diameter, and frost line height). An asterisk identifies the primary response to each increase.

Table 5.1 The Effect of Each Main Process Variable on Bubble Geometry

Variable to increase	Film thickness	Bubble diameter	Frost line height
Nip speed	↓ *	↑	↑
Screw speed	↑ *	↑	↑
Cooling speed	↑	↓	↓ *
Bubble volume	↓	↑ *	↓

* Primary response

This table highlights how making one adjustment in the process affects all three of the bubble characteristics. A skilled operator must understand these interrelationships to accurately adjust the process so that all the geometry requirements are within specification. Even though many blown film lines today are automated to adjust for changes in process conditions, the above relationships still exist and it is the responsibility of the system (manual or automatic) to take the proper corrective action.

Simulator Exercise: Try increasing each of the four variables in the table individually. During each increase, observe the effect on each quantity in the measurements panel. It may be beneficial to record and plot, using spreadsheet software such as Excel, the values with each change to see which measurements are affected most by each adjustment.

In the following paragraphs, a description is given of each of the relationships identified in Table 5.1. The assumptions here are:

1. only one process variable increases at a time while the others remain constant and
2. each response occurs naturally without correction from a closed-loop control (automatic measurement and adjustment) system.

When the nip speed increases, the primary effect is for the melt to be stretched more in MD, making the film thinner. As a result of the film traveling past the cooling air more quickly, the height on the bubble where the temperature has dropped to the point of polymer solidification (the frost line) increases. (It is easy to mistakenly think that the frost line height should decrease because thinner film must cool faster. However, this is not the case because the effect of an increase in film speed is more significant and the frost line height always increases.) As the frost line height increases, the small diameter stalk below the frost line lengthens and the air volume in the bubble is displaced more to the top, because the bubble contains a fixed volume of air. This increase in bubble volume above the frost line pushes the bubble outward to a higher diameter, also contributing to film thinning.

An increase in screw speed results in an increase to all three bubble geometry variables. The increase in output from the extruder has the primary effect of increasing film thickness. Also, a greater amount of material results in a greater amount of heat that must be removed from the film. This takes a longer time under constant cooling conditions, thus increasing the frost line height. Again, as the frost line moves upward, the bubble diameter increases. The slight thinning effect due to an increase in bubble diameter is far outweighed by the thickness increase created by greater output.

Increasing the cooling air speed causes faster heat removal from the bubble. Because the film reaches solidification temperature sooner, the primary effect is a lowering of the frost line. As a result, the bubble diameter decreases from the constant internal air volume being distributed over a greater distance from frost line to nip rollers. Because a lower bubble diameter means the film is not stretched as much in TD, the film thickness increases.

When more air is inserted into the bubble, the bubble volume increases; primarily the diameter increases by stretching more in TD. The increased TD stretching results in thinner film. Thinner film cools more quickly, consequently lowering the frost line height.

5.2 Characteristic Bubble Ratios

To properly describe and control the bubble-forming process, certain quantities have been developed to characterize the process conditions that influence bubble geometry. These quantities are the take-up ratio (TUR), the blow-up ratio (BUR), and the forming ratio (FR).

The TUR is the ratio of film velocity (V_f) to melt velocity (V_m), i.e., TUR = V_f / V_m. This quantity provides an indication of the amount of stretching, hence molecular orientation, in MD. The film velocity is the upward speed of the film above the frost line and is established by the control system. It is equivalent to the nip speed. The melt velocity is the upward speed of the molten polymer as it exits from the die lips. It is related to, but is not equal to, the screw speed. The melt velocity can be determined experimentally by marking the film and tracking the mark, but an easier method is to employ the principle of conservation of mass.

The conservation of mass states that the mass flow rate (pounds/hour) is equal at all points along the bubble. Mathematically,

$$m_{\text{rate}} = (\rho\, A\, V)_{\text{nip rollers}} = (\rho\, A\, V)_{\text{die gap}} \tag{5.1}$$

where ρ = density, A = annular area, V = velocity.

This equation can be rearranged to the form

$$\text{TUR} = V_{\text{f}}/V_{\text{m}} = (\rho\, A)_{\text{die gap}} \big/ (\rho\, A)_{\text{nip rollers}} \tag{5.2}$$

The area of an annulus (Figure 5.1) can be calculated from the following equation:

$$A_{\text{annulus}} = \pi\left(R_{\text{o}}^2 - R_{\text{i}}^2\right) \tag{5.3}$$

where R_{o} is the outside radius and R_{i} is the inside radius of the annulus.

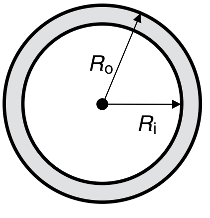


Figure 5.1 Area of an annulus: $A_{\text{annulus}} = \pi\,(R_{\text{o}}^2 - R_{\text{i}}^2)$

Since the nip speed is always greater than the melt speed, the TUR is always greater than one.

The BUR is the ratio of bubble diameter (D_{b}) to die diameter (D_{d}), i.e., BUR = $D_{\text{b}} / D_{\text{d}}$. This quantity provides an indication of the amount of stretching, hence orientation, in TD. The bubble diameter is established by the control system and can be either measured directly or calculated by measuring the layflat (LF) width directly (D_{b} = 2 LF / π). The die diameter is fixed.

Index