5 Extrusion Equipment

The plasticating extruder is the centerpiece for the production of continuous thermoplastic foam. The configuration of the extruder depends on the density of the final product and whether the foaming agent is chemical or physical.

5.1 Extrusion of Higher Density Foam

5.1.1 The Single-Screw Extruder

The single-screw extruder is used extensively when thermally stable high-density foam is produced using a chemical foaming agent.

As shown in Fig. 5.1, the single-screw extruder consists of a heavy-wall steel cylindrical barrel that is fitted with a flighted auger-like cylindrical screw. The barrel is heated with electric bands that are individually temperature-controlled. Sometimes the screw is heated, usually with hot oil or occasionally electrically. The screw is driven by a speed-controlled electric motor operating through a gearbox. A heated shaping die is attached to the far end of the barrel. The ingredients of the foam recipe are fed into the flights of the screw through a hopper or opening in the barrel at the motor end. The plastic is fed as either powder or pellets. When powder is used, an auger or crammer is often added to the hopper to force the powder against the feed screw flights.

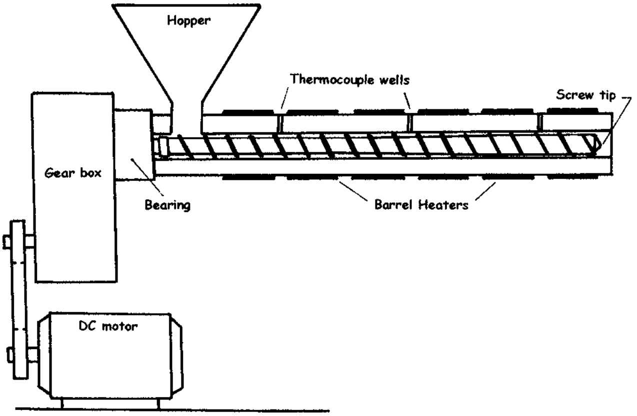

Figure 5.1 General schematic of conventional single-screw extruder for chemically blown high-density foam

If the chemical foaming agent is a dry powder, it is usually dry-blended with the plastic prior to feeding to the hopper. If the chemical foaming agent has been compounded with a plastic carrier as a masterbatch, it is metered directly into the hopper with the plastic. Other additives, such as nucleating agent and cell stabilizer, either are dry-blended with the plastic prior to feeding to the hopper or are metered directly into the hopper with the plastic. For long runs, it is recommended that all additives and foaming agents be compounded into the plastic prior to production. Fillers and reinforcements should always be compounded into the plastic prior to production.

5.1.1.1 The Single-Screw Extrusion Process

5.1.1.1.1 General Terms

A standard single-screw extruder can be envisioned as having three general zones, as detailed in the following. Extruders are frequently identified in terms of their L/Ds or barrel length-to-internal diameter. Extruders running high-density foam typically have total L/Ds ranging from 18 to 42. Heat transfer to the barrel is usually zoned into 4 to 10 zones. The barrel at the hopper is usually water-cooled to prevent premature melting and bridging of the polymer being fed to the extruder.

Typically, a large-horsepower electric motor drives a variable-speed drive train that reduces the 1750 revolutions per minute or RPM motor speed to typical screw speeds of 15 to 200 RPM. Newer extruders use solid-state variable speed DC motors or single-unit hydrostatic drives instead of motors and gear boxes.

The screw flights form a continuous spiral channel from the feed or motor end of the barrel to its die end. For most screw designs, the channel width or spacing between the flights is constant throughout its length. The channel depth, on the other hand, decreases in stages from the feed end of the barrel to the die end.

The polymer powder or pellets and other ingredients drop into the deep channel and are conveyed down the channel by the drag of the screw. The solid particles compact readily in the first few turns of the screw. As a result, the solids bed behaves as a plug as it moves down the spiral channel. This portion of the extruder is sometimes called the drag-induced solid bed conveying section or just solids conveying zone. The effectiveness of down-channel solid bed transfer is a function of the friction between the solid polymer bed and the metal surfaces. The bed is moved down the channel with friction between the barrel and the bed and is retarded with friction between the bed and the screw. Low frictional coefficient values are achieved by plating or polishing the screw root and flights or by applying low-friction fluoropolymer coatings. High frictional coefficient values at the barrel surface are achieved by roughening or grooving the barrel and by increasing or maintaining high barrel temperatures in the solids conveying zone. The solids conveying zone may be 4 to 10 barrel diameters or L/Ds in length. Two heating zones are preferred.

Frictional heat generation between the sliding bed and the barrel surface raises the temperature of the polymer surface to the melting point. When a thin film of molten polymer exists between the bulk of the solids bed and the barrel surface, solid-to-solid friction ends. At this point, the liquid layer experiences intense shear and viscous energy generation acts to rapidly increase the liquid layer thickness. Because the screw rotates as the ingredients move in the spiral channel, the liquid flow motion is no longer plug. Instead, a spiral motion within the channel begins. The melting polymer accumulates in a pool between the solid bed and the pushing flight or the flight at the rear of the channel. This forces the solid bed against the trailing flight or the flight at the front of the channel. In certain cases, the solid bed may actually break into pieces. This phase of extrusion is called plastication or melting.

The channel depth decreases in the plasticating zone and perhaps for several turns before that. This is known as compression. Some compression is needed since the solid ingredients that are fed to the extruder have bulk densities less than the fully compacted solid. Some compression is used to build downstream pressure to aid compaction of the solid bed and viscous heat generation. The degree of compression is called the compression ratio. High compression ratios and short compression sections are used when polymers tolerate high levels of viscous heat generation and polymers that melt in narrow temperature ranges. Polyethylenes can be extruded with high compression ratio screws. Low compression ratios and long compression sections are used for thermally sensitive polymers and polymers that do not melt or become liquid in narrow temperature ranges. Polystyrenes, PVCs, and PETs usually do best with lower compression ratio screws. The typical plasticating zone may be 10 to 20 barrel diameters or L/Ds in length. Three heating zones are preferred but two are acceptable.

When essentially all the solid polymer has melted, the melt is conveyed to the die. This portion of the screw is called the melt-conveying zone. In this zone, sufficient pressure is built to force the melt through the constrictions up to and including the die. Viscous drag flow is the primary means of conveying the melt down the spiral channel to the die. Pressure flow retards melt flow. Shallow channel depth favors viscous drag flow. By far the majority of energy supplied to the extruder in viscous drag flow dominated extrusion is dissipated as heat into the polymer and metal. The melt conveying zone may be 4 to 12 barrel diameters or L/Ds in length. Two heating zones are preferred but one may be acceptable as long as heat is provided for the plumbing between the barrel end and the die block.

5.1.1.1.2 Chemically Blown Foam Extrusion

The process outlined above is used extensively to produce a high-density foam product using a chemical foaming agent. As the plastic is conveyed down the barrel, it is heated by the barrel and by internal friction. It melts or plasticates and the melt pressure builds. Once the polymer is fully melted, the melt temperature is raised until the chemical foaming agent decomposes. If the chemical foaming agent decomposes before the polymer is fully melted, the blowing gas may find its way back up the spiral channel to the solids conveying zone and ultimately the hopper.

The melt containing the dissolved blowing gas is pumped under pressure through an opening in the far end of the barrel and into the shaping die. As the melt passes through the die, its pressure falls and the dissolved gas quickly forms microbubbles. Melt pressure must remain as high as possible for as long as possible to minimize premature foaming of the polymer inside the die.

The extrudate exiting the die expands until the internal cell gas pressure balances the external pressure or until the extrudate contacts a downstream shaping die. Air- and/or water-cooling rigidifies the foam. The foam is then cut to length or for certain profiles such as foam pipe or cable, wound onto reels. A typical high-density foam extrusion line is shown in schematic in Fig. 5.2.

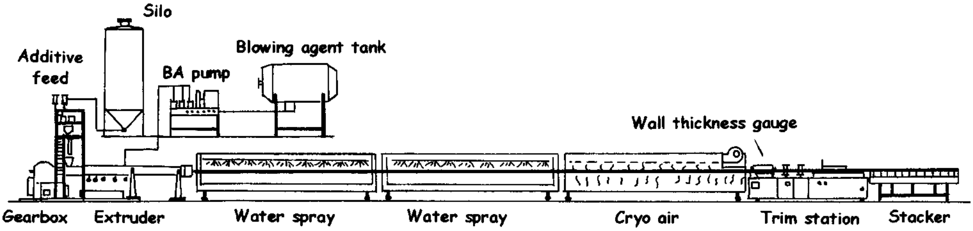

Figure 5.2 *General schematic of physically blown foam extrusion line*

5.1.1.2 Extruder Size and Throughput

Extruders are primarily sized by barrel diameter. Extruder lengths of 28 to 42 barrel diameters or L/Ds are recommended for most high-density foam profile extrusion. Although ¾-inch extruder barrel diameters are manufactured, the smallest commercial extruder barrel diameter is about 60 mm or 2-½ inches. An extruder of this size, operating at around 80 revolutions per minute or RPM processes about 40 kg/h (90 lb/h) LDPE pipe foamed to about 600 kg/m^3 (35 lb/ft^3). A 150 mm or 6 inch diameter commercial machine turning at 25 RPM would process about 300 kg/h (650 lb/h) of this product. Typical extruder sizes and throughputs are given in Table 5.1.

Occasionally the output rate from a single-screw extruder may vary at a frequency similar to the screw speed. The uneven flow is often called surging. High extruder throughput may be causing surging because of intermittent solid bed breakup instability. One way of overcoming these problems is to install a gear pump or melt pump between the barrel exit and the die inlet, see Fig. 5.3. The gear pump or melt pump is a near-positive displacement pump that can also substantially increase melt pressure to the die inlet. Gear pumps generate substantial viscous heat and they are not self-cleaning. As a result, gear pumps are not recommended for use with thermally sensitive polymers such as PVC and PET.

Table 5.1 *Performance Criteria for 38 : 1 to 42 : 1 L/D Single-Screw Extruders Producing Foamed LDPE Sheet of 70 to 250 kg/m^3*

Screw diameter (mm)	Screw speed (RPM)	Drive power (kW)	Maximum throughput (kg/h)	Sheet width (mm)	Sheet thickness (mm)
45	120	13	35	1000	0.15–3.00
60	80	20	70	1500	0.15–3.00
90	45	38	135	1800	0.50–3.50
120	30	65	215	1800	1.50–3.50
150	22	95	310	1800	1.50–3.50

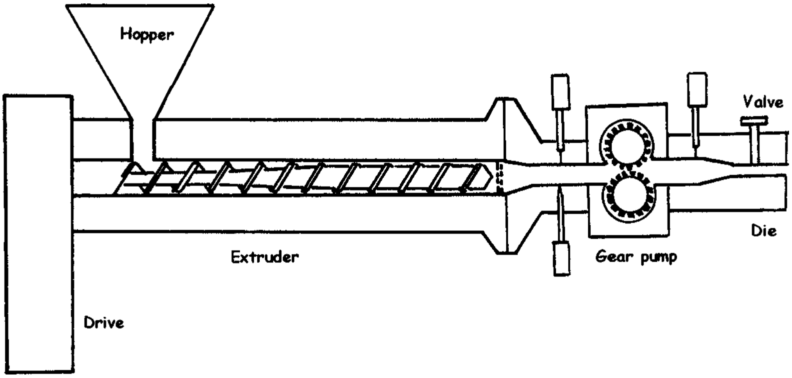

Figure 5.3 *High-density foam extrusion system with gear pump*

5.1.2 The Twin-Screw Extruder

Twin-screw extruders are used to process thermally sensitive polymers and additives. There are many variations of twin-screw extruders. The screws can be cylindrical, as is the case with the screw in a single-screw extruder. Alternatively, they can be conical, see Fig. 5.4. Conical twin-screw extruders are primarily used to process PVC or other thermally sensitive polymer foam. Conical twin-screw extruders are used extensively in wire and cable applications.

If the two screws turn in the same direction, the extruder is called a corotating extruder. It is primarily used in compounding polymers and additives. Screw speeds are very high, up to 1000 RPM or more. If the two screws turn in opposite directions, the extruder is called a counter-rotating extruder. Most high-density foam twin-screw extruders use counter-rotating screw configurations. The extent of intermeshing of the two screws is also a design feature. Most high-density foam twin-screw extruders use fully intermeshing screws. The intermeshing feature enables the polymer melt to be wiped clean of the screw flights. Although twin-screw extruders can have lengths greater than 50 L/D, foam extruder lengths are typically around 30 L/D. Although compounding twin-screw extruders run at screw speeds exceeding 500 RPM, foam profile extruder screw speeds are typically 20 to 50 RPM.

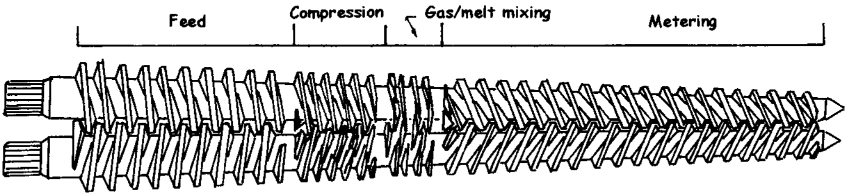

Figure 5.4 *Conical twin-screw configuration for thermally sensitive foamable polymers*

Single-screw extruders are flood-fed. That is, polymer should always be present in the hopper for the extruder to advance the polymer melt through the barrel and die. Because the flow of polymer through a single-screw extruder is drag-flow, the throughput rate of a single-screw extruder is tied directly to the screw speed. Twin-screw extruders are near-positive displacement melt pumps. They can be starve-fed. Starve-feeding decouples the throughput rate of the extruder from the screw speed. Nevertheless, twin-screw extruders used to produce foam profiles are often run in a flood-fed mode.

Many different geometries are used in twin-screw extruders, unlike the typical single-screw extruder screw that has rather simple parallel flights with gently changing channel depths. The variety of geometries and the general complex flow patterns in twin-screw extruders make careful analysis of polymer transfer from screw element to screw element very difficult. This in turn makes it difficult to predict throughput rate and pressure for various polymer properties, and melt temperatures.

Many fully intermeshing counter-rotating twin-screw extruders are of modular design. That is, the screws and, at times, the barrel have removable modular segments. Flighted elements similar in design to single-screw flights convey melt down the barrel. They are self-wiping. Restrictive or left-hand elements provide backpressure. Kneading elements mix the melt and are self-wiping. Kneading elements can be designed to just mix, mix with some conveying, or mix with some restriction. The plasticating and mixing efficiency of a twin-screw extruder depends on the proper selection of mixing, wiping, transfer, and pressure developing elements. Modular barrel segments allow additives such as fillers, cell stabilizers, and foaming agents to be added after the plastic has been thoroughly plasticated or melted.

Good screw design is necessary to ensure that high melt pressure is maintained once the foaming agent is added to the melt. Unfortunately, the complexity of polymer flow from element to element and the many ways of combining the various types of elements restrict prediction methods to either oversimplified guidelines or very complex computer analyses. In addition, twin-screw extruders are considerably more expensive than single-screw extruders. As a result, twin-screw extruders are primarily used when the polymers are shear- or thermally-sensitive, when large quantities of additives, fillers, or reinforcements are to be mixed into the polymer, or when the polymer must be degassed.

Degassing, usually called devolatilization, is important when a portion of the polymer feed is regrind that contains moisture or blowing gas. Moisture is deleterious to certain polymers such as PET, polycarbonate, and nylons. Because the concentration of blowing gas and air in foam regrind is neither known nor controlled, devolatilization of these gasses is recommended. Because twin-screw extruders can be starve-fed, a portion of the screw flights may only be partially filled with polymer melt. This provides for substantial exposed surface area for vacuum venting of the undesired small molecules. For high-density foam extrusion, degassing takes place before the polymer melt temperature is increased to the point where the chemical foaming agent begins to decompose.

Although vented single-screw extruders are also available, single-screw extruder channels are usually completely filled with polymer melt. As a result, the surface area available for mass transfer is quite small. In addition, it is difficult to degas the melt before the chemical foaming agent begins to decompose.

5.1.3 Extruder to Die Transition

The transition between the extruder barrel exit and the entrance to the shaping die usually contains a breaker plate, screens, and an adapter that converts the cross-section of the extruder to that of the shaping die. The breaker plate interrupts the spiraling flow of polymer melt from the extruder screw and supports the screens. It also thermally homogenizes the polymer melt. Holes about 5 mm in diameter are drilled in the plate, to about 50% or more of the cross-section of the plate.

50- to 100-mesh welded wire screens are used to filter undesirable materials such as tramp metal, gels, and unmelted polymer from the molten polymer stream. Screens can be manually changed but most commercial extruders use mechanical screen changers that operate on pressure drop across the screen. Screens may not be needed when extruding large cross-section high-density foam profiles. Screens should not be used to build backpressure in the extruder.

Typically, the transition adapter should be short. Its cross-sectional area should be constant or decrease from the extruder exit to the die entrance. The breaker plate-adapter assembly should have at least one heating zone.

Since substantial pressure drop can occur across adapters, breaker plates, and screens, premature foaming can occur downstream of these constrictions. Pressure downstream of the adapter should be monitored and maintained as high as possible to prevent premature foaming.

5.1.4 The Profile Die

5.1.4.1 General Concepts

The extruder die shapes the extrudate. The region between the adapter and the exit end of the die forces the polymer melt into a uniform flow front. The die exit region is called the land. The land area completes the shaping of the melt. The very edge of the land area is often called the die lip.

For unfoamed polymers, extrusion die design is fairly well understood. Although there are many computer-assisted design programs available, final geometry of the die lip region is often obtained by subtle cut-and-try. Profiles with abrupt changes in wall thicknesses pose serious die design problems. As expected, polymers flow more readily through more open portions of the die than they do through narrower portions. As a result, flows are balanced with internal flow restrictors. Parts with complex profiles are produced best at one melt temperature, one die pressure, and one flow rate.

The primary design parameters include extrudate swell and drawdown. Extrudate swell is the polymer melt response to the transition from shear flow in the die to the zero shear field beyond the die. Polymers with high melt elasticity exhibit high extrudate swell. Drawdown is the result of mechanical stretching or pulling on the extrudate by the downstream equipment. Mechanical pulling is usually required to transport the extrudate through the downstream shaping and cooling machinery. Extrudate cooling can also change the shape of the profile. Thicker sections cool more slowly than thinner sections, resulting in distortion, warpage, sink lines, and internal voids.

5.1.4.2 High-Density Foam Dies

High-density foam extrusion offers greater die design challenges than does unfoamed polymer extrusion. Foam formation occurs at or just beyond the die land. As a result, in addition to extrudate swell and drawdown effects, there are substantial changes in extrudate cross-sectional area at very short distances from the die lip. If the foam is simply allowed to expand freely, the final profile dimensions are very difficult to control, even for profiles with very simple cross-sections. In short, without exterior constraints, the extrudate will attempt to become circular in cross-section. As a result, the preferred design method is to use the die to shape the polymer melt to an approximate shape, such as rectangle or oval, and create the final profile once the foaming polymer exits the die.

Two general methods are employed to produce accurate foam profiles. The more common method allows the foam to freely expand. The foamed extrudate is then shaped in a sizing die or calibrator, see Fig. 5.5. Friction sizing or drawing is used with unfoamed polymer profiles but is not normally used for high-density foam profiles because foamed polymer tends to be weak in tension. Vacuum sizing is the preferred method with the vacuum drawn through drilled holes, milled slots, or porous metal in the internal calibrator surfaces. The sizing die is usually water-cooled. For certain polymers such as polystyrene and polycarbonate, the internal calibrator surfaces are usually coated with a permanent low-friction agent. For other polymers such as polyolefins, the internal surfaces may be roughened or may have microgrooves cut in the draw direction. The final product is usually of uniform density with a very thin, higher density skin.

In a second method, the foam is not allowed to initially expand freely. Instead, the foam expands against the cool sizing die or calibrator walls. The walls rapidly cool the profile surface, thereby controlling its external profile dimensions and forming a high-density skin. As this is occurring, the core of the profile remains molten and blowing gas continues to expand the melt, see Fig. 5.6. The result is foam having a well-defined skin and a low-density foam core. The product is often called structural foam. Another version of the inward-foaming process is often called the Celuka process. Instead of allowing the foam to expand against the sizing die walls, the extrusion die contains a tapered mandrel inside a cooling sleeve. The skin of the extrudate is cooled while the core foams around the decreasing cross section of the mandrel, see Fig. 5.7. The Celuka process generally produces a high-density skin and an inner foam core with controlled cell size.

Strand foam extrusion uses a breaker plate or spinneret plate in place of a traditional extrusion die. Polymer melt is pumped through the small-diameter holes in the breaker plate. The individual extrudate strands foam on exiting the plate. The foaming strands are fed into a shaping die or calibrator, where the individual strands stick to one another, see Fig. 5.8. The final product has an apparent grain, and therefore this process was called the “Woodlite” process when it was developed nearly fifty years ago. This method is used to produce polystyrene and PVC foam millwork. A rod is the easiest profile to produce since the die is simply a hole drilled into a plate. Strand profiles are achieved when holes are drilled in a pattern in the plate. As a result, strand foam extrusion is used extensively in polymer development programs.

In general, it is difficult to fabricate complex profiles in foam. Designs with sharp corners, large aspect ratio sections, or profiles with great differences in local cross sections should be avoided.

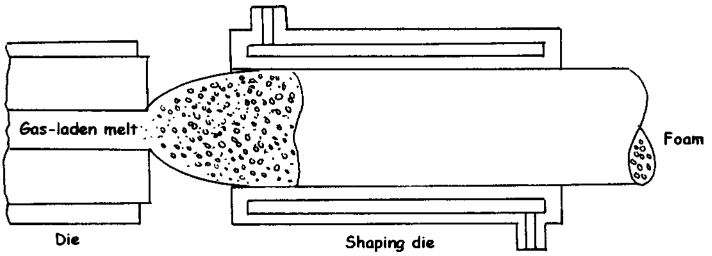

Figure 5.5 High-density foam freely expanded and shaped in calibrator or shaping die

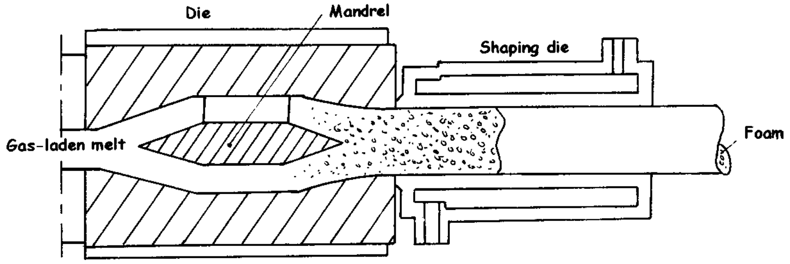

Figure 5.6 High-density foam with foaming occurring at end of internal mandrel

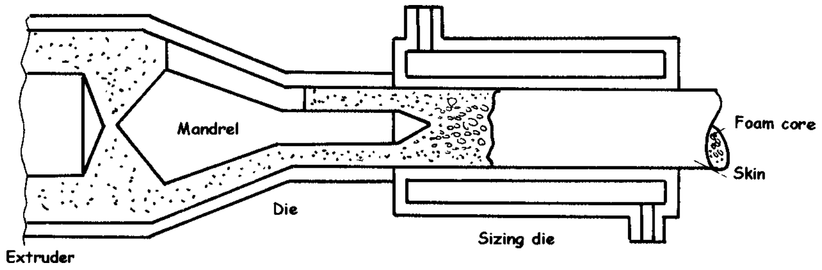

Figure 5.7 High-density foam profile with high-density skin and low-density foam core (Celuka process)

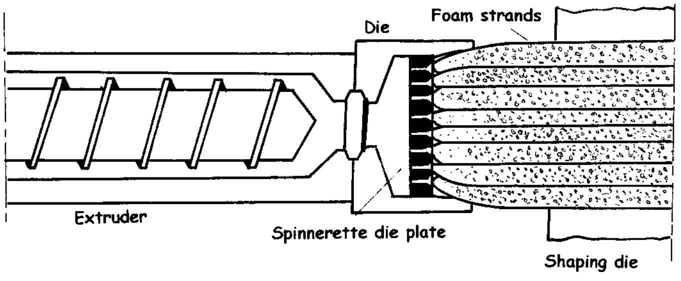

Figure 5.8 Strand foam produced using spinnerette die and calibrator or shaping die

5.1.5 Sheet and Pipe Dies

High-density foam sheet is used in thermoforming applications. Conventional unfoamed plastic sheet dies are used to produce high-density foam sheet, so long as the sheet density is only a few percent less than that for the unfoamed plastic. The coat hanger die is commonly used with high-density foam, see Fig. 5.9. As with all quality sheet products, the optimum die design yields uniform polymer melt flow at the die exit. As expected, however, uniform flow characteristics for a given polymer are achieved at unique processing conditions, including melt temperature and die pressure. Flexible die lips are used to balance flow distribution through the die lips. Short land lengths are used to minimize premature foaming in the die. The foamed sheet usually is cooled first by casting it against standard sheet extrusion chill rolls. Extrusion into the nip region on the roll stack tends to minimize nonuniform foam expansion, particularly in the center of the sheet. The nip gap should be set to minimize nonuniform foam expansion without building a bank behind the rolls, because a bank will cause cell coalescence and foam collapse.

Foams produced on conventional sheet die lines typically have substantial high-density skins and relatively thin foam cores.

High-density foam pipe is an important commercial business. A foam pipe die is similar in design to a die for unfoamed pipe. Essentially, the polymer melt flows through an annular die, with the internal mandrel or center section extending some distance beyond the die body inlet, see Fig. 5.10. The temperature of the internal mandrel is carefully controlled. The method of holding the internal mandrel in place in the die body is the key to successful foam pipe manufacture. The internal mandrel support post is called a spider or spider leg. For small-diameter pipes, the internal mandrel is supported with a single spider leg. With very large-diameter dies, the internal mandrel may be supported by three or four spider legs. The spider leg separates the flow stream, which must be rewelded or reknitted to ensure uniform pipe wall thickness and strength. This is accomplished in the die flow channel downstream of the spider leg. Spider leg streamlining also aids re-knitting.

Re-knitting must be done before the polymer melt pressure decreases to the point where microbubbles are forming. It may be very difficult to achieve good reknitting if the polymer melt is highly elastic, as is the case with many polyethylenes. A poorly reknitted profile will exhibit a spider leg "witness line" along the profile length. Concentricity is achieved through adjusting bolts on the internal mandrel spider leg.

Foam pipe dies are usually followed by sizing dies or calibrators. Although internal air pressure is used to press unfoamed pipe against the calibrator, excessive pressure on the still-soft foam pipe may collapse the foam. As a result, vacuum sizing is commonly used, with auxiliary low-pressure internal air used to keep the pipe round.

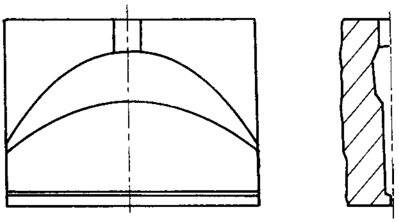

Figure 5.9 *Traditional coat-hanger die for high-density foam sheet*

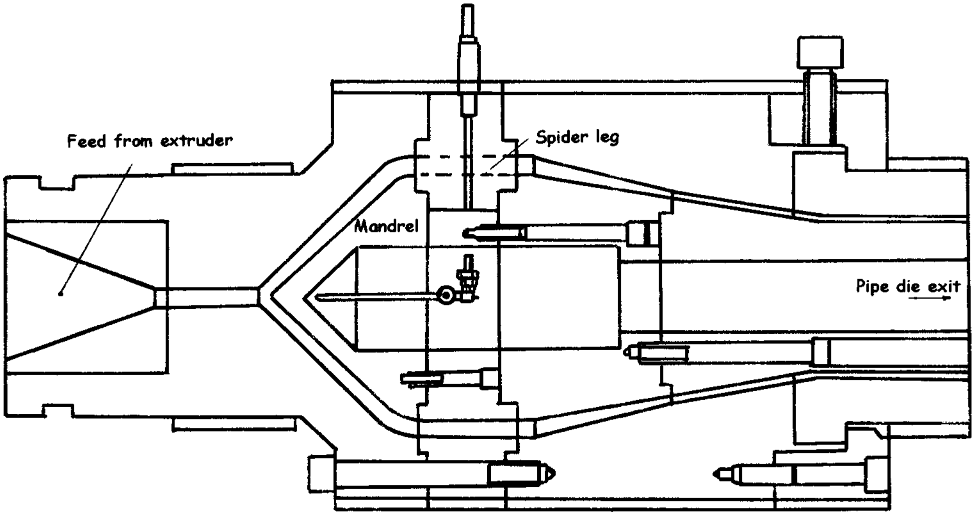

Figure 5.10 High-density foam pipe die

5.1.6 Wire Coating Die

Many commercial products require thermal or electrical insulation jackets. Electrical and electronic cable, flexible conduit, rope, and fiber optic cable are some examples. A crosshead extrusion die is used for this application, see Fig. 5.11. In essence, the metal wire, rod, or tube acts as a moving mandrel, with the molten polymer flowing around it as it is pulled or pushed through the die body. As with all foam processes, the melt is under pressure throughout the die. Foaming occurs beyond the die exit. The extrudate usually passes through a sizing die or calibrator and subsequent cooling water baths before being wound on cable reels. The die flow channel must be carefully designed to equalize polymer melt flow around the wire, since the polymer enters on only one side of the crosshead die.

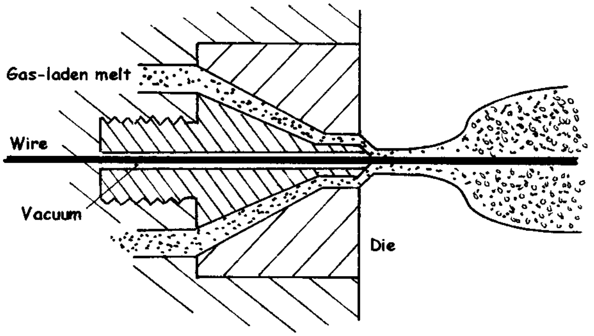

Figure 5.11 Schematic of wire-coating or crosshead die with vacuum seal

5.1.7 Cooling the Foam

Typically, the sizing die or calibrator is jacketed and water-cooled. This rigidifies the surface of the foam but the core remains molten. The foam is further cooled with water, either completely immersed in a circulating water tank or in a spray or shower tunnel. Chilled or cryogenic air is not as effective a cooling medium as water. Rapid cooling will cause the skin to thicken and will lead to coarse or even collapsed interior cells. The key to heat removal is the ratio of the heat removal effectiveness of the coolant fluid to the thermal conductivity per unit thickness of the foam. For most coolant systems and for moderately thick foam sheets and profiles, the rate of heat removal from the plastic is the controlling factor in cooling. The rate of heat removal from the sheet or profile is a function of the thermal diffusivity of the foam. The thermal diffusivity value for a given high-density foam is about the same as the value for the unfoamed polymer. In general, the thermal diffusivity values of polymers are a thousand times smaller than those for metals. This means that the sheet or profile surface temperature quickly attains the temperature of the coolant but the internal temperature remains elevated for extended periods.

Once optimized, the cooling bath length is proportional to the square of the foam profile thickness and directly proportional to the line speed.

5.1.8 Take-Off Equipment

The method of pulling the foam from the die through the calibrator depends on the general shape, density, and rigidity of the foam. Double belt, double wheel, or caterpillar pullers are used for rigid pipe and profile. For flexible pipe and profile, caterpillar pullers are used immediately after the foam exits the cold-water tank. Banks of nip rollers are used for rigid plank. In most cases, rigid high-density foam products are crosscut with carbide bladed circular saws and stacked. In others, the cooled foam products are wound on very large diameter spools.

5.2 Extrusion of Low-Density Foam

Products made from low-density foams often begin as extruded sheet or plank. Sheet is considered to be less than 15 mm or ½-inch thick. Polyethylene and polypropylene thin-gauge sheet is used as protective wrap. Polystyrene thin-gauge sheet is heated and thermoformed into insulative and protective packages and containers. Plank is usually greater than 15 mm or ½-inch in thickness. Polyolefin planks are cut and glued into shock mitigating dunnage or heated and bent into large-diameter thermal insulating pipe collars. Polystyrene planks are used in construction as thermally insulating panels.

Low-density foamed sheet and plank are produced on similar equipment, but the die designs are different.

5.2.1 Tandem Extrusion

In North America, tandem extrusion is the primary method of producing low-density foams. In tandem extrusion, the output of the first extruder is the input to the second. The shaping die is attached to the exit of the second extruder.

5.2.1.1 The Primary Extruder

In tandem extrusion, the first extruder is usually a single-screw extruder similar to that used for high-density foam extrusion, see Fig. 5.12. The first extruder is often called the primary extruder. The polymer and additives are hopper-fed to the screw through an opening in the heated barrel. The screw augers the polymer through the traditional solids conveying, plasticating, and melt pumping phases. The melt pumping zone may be substantially shorter than that in conventional extrusion. These phases occupy 18 to 24 barrel diameters or L/Ds. Primary extruder screw speed may vary from 50 to 150 RPM.

When the polymer is melted, a physical foaming agent in the form of blowing gas or volatile liquid is introduced under pressure into the melt through a hole in the barrel wall. The hole is called the gas inlet port. In this region, the screw design might be changed to accommodate the foaming agent. For example, a restriction called a blister or blister ring may be placed up-stream of the gas inlet port. The blister provides a barrier to prevent injected gas from flowing toward the hopper end of the extruder. The flow channel depth may also be increased. Because the flow rate is fixed, increasing the flow channel cross-section results in a lower pressure. This allows the gas to be injected at lower pressures than those developed during the plasticating and melt pumping phases. However, melt pressure should be high enough to ensure that the foaming agent is introduced as a supercritical fluid.

Interrupted flights, mixing pins, and barrier elements on the screw intimately mix the foaming agent with the molten polymer. In addition, melt pressure is rebuilt by pumping the polymer through conventional spiral flow channels. The primary extruder may incorporate a breaker plate and screens. The pressure drop across these elements must be monitored to minimize premature foaming.

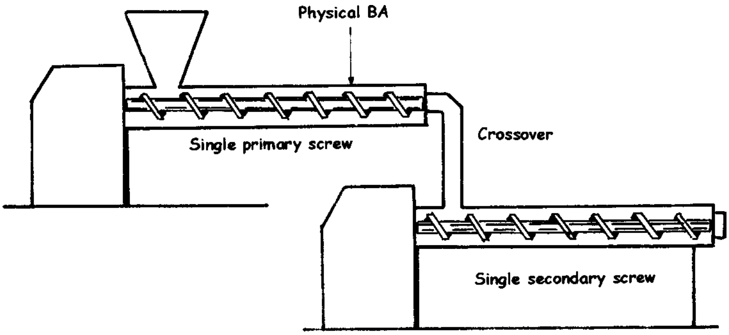

Figure 5.12 Single-screw primary extruder in tandem extrusion system, for low-density foam

Occasionally a melt pump or gear pump is used between the primary and secondary extruders to minimize melt flow and pressure surging. Because the gear pump is a near-positive displacement pump, it is also used to boost melt pressure. This is important because the viscosities of polymers containing dissolved gas are much less than the same polymers without dissolved gas.

5.2.1.2 Twin-Screw Primary Extruders

Twin-screw extruders are used as primary extruders for processing thermally sensitive polymers, see Fig. 5.13. A physical foaming agent is introduced at a port downstream of restrictive screw elements. Kneading elements are mixed with forwarding elements to ensure gas dispersion and melt homogeneity as well as adequate melt pressure. A melt pump or gear pump may be used at the barrel exit to boost pressure to the secondary equipment. Although modular twin-screw extruders have great flexibility and are efficient in solids conveying and plasticating, they have certain disadvantages:

- They are expensive
- It is difficult to generate substantial transfer pressures
- The proper selection of elements is not easily determined

5.2.1.3 The Transfer Pipe

In an optimum scheme, the polymer and foaming agent are homogeneous at the exit end of the first extruder but the polymer melt temperature is too high to allow stable foaming to take place. As a result, a second extruder is used to lower the melt temperature while maintaining melt pressure to prevent premature foaming, see Figs 5.12 and 5.13. The second extruder is often called the secondary extruder. Transfer of the melt from the primary to secondary extruder is best achieved by coupling the primary extruder barrel exit directly to the secondary extruder barrel entrance, see Fig. 5.14. This T-shape configuration uses more

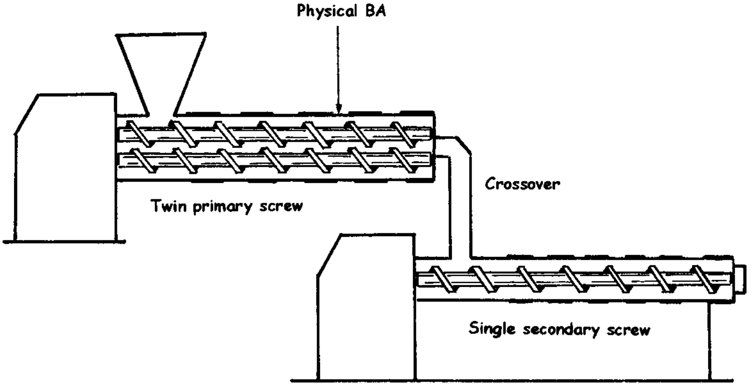

Figure 5.13 *Twin-screw primary extruder in tandem extrusion system, for low-density foam*

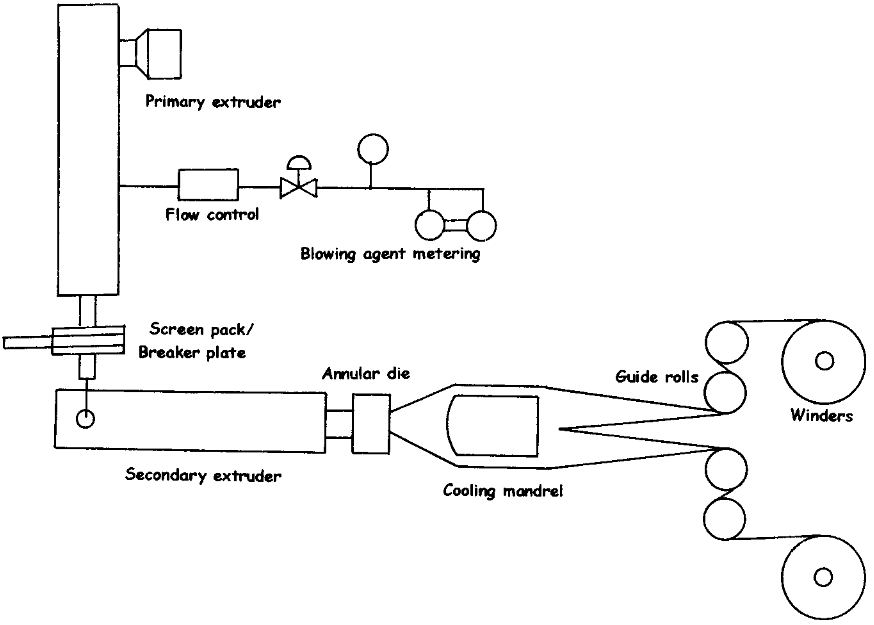

Figure 5.14 *T-style tandem extrusion system, eliminating right-angle crossover or transition pipe*

floor space than that used by side-by-side extruders. As a result, nearly all commercial tandem installations use side-by-side extruders. These extruders are coupled with an L-shaped transfer pipe, see Fig. 5.12. The transfer pipe is heated and the L-shaped flow channel must be gently radiused to minimize stagnant polymer melt areas and thermal inhomogeneity. The cross-section of the transfer pipe must be smaller than the cross-section of the exit flow channel of the primary extruder. Many processing problems can be traced to a transfer pipe that is not adequately heated, is too large in diameter, or has a severe radius.

5.2.1.4 The Single-Screw Secondary Extruder

In North America, the secondary extruder is usually a single-screw extruder driven by a separate motor and gearbox. Its design is unlike that of conventional extruders. Because the extruder is not solids-conveying or plasticating, the screw channel depth is constant. The screw may be multi-flighted and may have shallow flight depths. These features increase the relative surface area of the melt against the barrel wall and screw root. Improved screw designs incorporate interrupted flights, mixing pins, and slots at the bases of screw flights. The flow stream is split and reoriented by these distributive-mixing elements. This improves melt temperature uniformity. However, temperature control improvement must be balanced by the loss in pumping efficiency. The secondary extruder barrel diameter is larger than that of the primary extruder, and the screw turns slower. The secondary screw speed may vary from 10 to 40 RPM. This reduces frictional heating of the polymer melt and provides greater surface area for temperature control.

The barrel temperature is regulated through a combination of heating and cooling elements. Typically, the secondary extruder temperature control system is separated into three to as many as six zones, not including the transfer pipe or the die block zones. In large secondary extruders, the screw should be cored for water-cooling. The rear bearings of the secondary screw must be sealed against the high-pressure of polymer melt containing blowing gas.

Characteristics of single-screw tandem extruders are given in Table 5.2. Tandem primary/secondary extruder barrel diameters are traditionally matched in inches as 2½ / 3½, 3½ / 4½, 4½ / 6, 6 / 8, and 8 / 10 or 8 / 12, or in millimeters as 45 / 60, 60 / 90, 90 / 120, 120 / 150, 150 / 200, and 200 / 250. Typical length-to-barrel diameter ratios are 28 : 1 to 36 : 1. Typical screw speeds are approx. 100 RPM for the primary extruder and 25 RPM for the secondary extruder. Typical melt pressures are 3000 psi to 6000 psi or 20 to 40 MPa.

Table 5.2 *Performance Criteria for Tandem Single-Screw Extruders Producing Low-Density LDPE Sheet*
Primary Screw, I: 24 : 1 to 32 : 1 L/D
Secondary Screw, II: 28 : 1 to 30 : 1 L/D
Foam Density: 70 to 250 kg/m³ (unless noted differently)

Screw diameter (mm) I	Screw diameter (mm) II	Screw speed (RPM) I	Screw speed (RPM) II	Drive power (kW) I	Drive power (kW) II	Maximum throughput without melt pump (kg/h)	Maximum throughput with melt pump (kg/h)	Sheet width (mm)	Sheet thickness (mm)
45	60	240–400	19–35	31	13	80	–	1500	0.15–3.00
60	90	180–300	15–28	90	22	150	–	1800	0.15–3.50
90	120	120–190	13–23	90	40	240	265	1800	0.15–3.50
120	150	90–140	11–20	135	60	400	450	1800	1.5–100*
150	200	72–112	10–17	180	115	620	700	1800	1.5–100*

* 38 to 250 kg/m³

5.2.1.5 Other Secondary Conditioning Equipment

For certain product applications and many thermally sensitive polymers such as PVC, a short twin-screw extruder is used as the secondary extruder. Although twin-screw extruders provide superior homogenization of the melt containing dissolved gas, they do not cool the melt as efficiently as single-screw extruders do.

In one commercial process for low-density polyethylene plank, thermally jacketed flat plate heat exchangers are used to cool the polymer. In development and small-scale production facilities, thermally jacketed static mixers are used to cool the polymer, see Fig. 5.15. The flat plate heat exchanger and the static mixer secondary unit cannot generate melt-pumping pressure. As a result, the pressure of the melt delivered to the extrusion die may not be sufficient to minimize premature foaming. Process conditions developed for laboratory extrusion systems using static mixers cannot be extrapolated to production tandem extrusion lines.

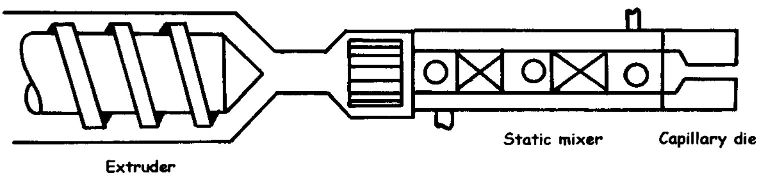

Figure 5.15 *Laboratory extrusion system, using thermally jacketed static mixer rather than secondary extruder*

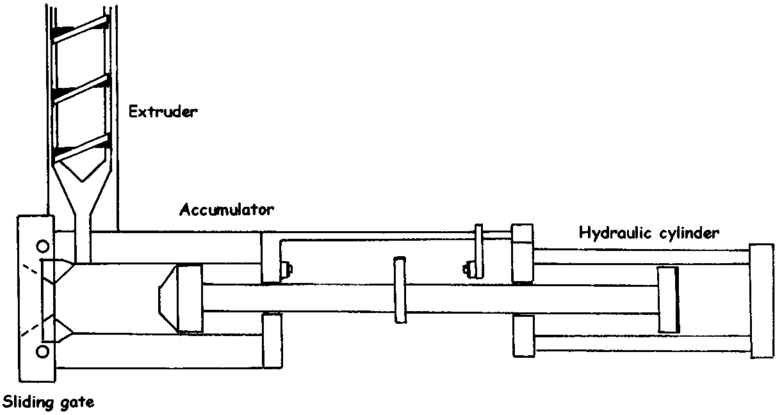

Figure 5.16 *Accumulator extrusion system for low-density foam plank production*

In another commercial process, a melt accumulator is used to produce foamed polystyrene and polyolefin plank. The accumulator is a barrel containing a piston and a high-pressure sliding gate valve, see Fig. 5.16. The extruder is similar to the primary extruder with the pressurized melt metered directly into the accumulator barrel. As the accumulator fills with pressurized melt, the piston is pushed back. When a desired shot weight is reached, the piston advances against the melt and the gate valve is opened. A check valve prevents the melt from being pumped back into the extruder. The melt is pumped from the accumulator onto a traveling belt where foaming occurs. When the accumulator is empty, the gate valve closes and the accumulator begins to fill again. When the plank is cool, it is trimmed to final dimension. While this system eliminates downstream plank cutting, it typically generates more trim stock than continuous take-off equipment.

5.2.2 Long Single-Screw Extrusion

A long single-screw extruder, often called a two-stage single-screw extruder, is sometimes used to extrude low-density foams. The extruder screw length-to-barrel diameter ratio or L/D often is 42 to 60. Solids conveying, plasticating, and melt pumping occurs in about the first half of the barrel length. A physical foaming agent is injected in a letdown zone in the screw. A short mixing section follows. The melt is then cooled in the remaining portion of the barrel length. The screw flights in this portion may be interrupted and mixing pins may be used to thermally homogenize the melt.

The advantage of a long single-screw extruder is that only one drive unit and one set of bearing seals are required. The primary disadvantage is that normal plasticating screw speed results in viscous heat dissipation in the melt in the cooling portion of the barrel. As a result, polymer throughput rate is limited by melt cooling capacity of the second portion of the extruder.

5.2.3 Foaming Agent Platform

When chemical foaming agents are used, they are added to the primary extruder hopper as metered additives. Other additives such as cell modifiers and antistatic agents are also metered into the hopper. Metering of compounded master batches is desired. Physical foaming agents are metered from supply tanks to the polymer melt through an orifice in the primary extruder barrel wall. Liquids are more easily pumped and metered than atmospheric gases, see Fig. 5.17. Nitrogen is usually delivered as a cryogenic liquid. It is vaporized and heated before being dispensed to the extruder. Carbon dioxide is also delivered as a liquid. It may be dispensed either as a liquid or vaporized and dispensed as a gas. Flow rates of gases and liquids are controlled with mass flow meters, see Fig. 5.18. Typically, physical foaming agents are pumped into the extruder at pressures of about 5000 psi or 35 MPa using two- or three-stage positive displacement pumps. Inlet lines may be electrically traced and insulated.

Many commercial installations have provisions for dispensing more than one physical foaming agent. Although these foaming agents may be mixed prior to injection into the extruder through a single port in the barrel wall, a more desirable practice is to inject multiple foaming agents through separate ports. This provides better flow monitoring and control of individual streams.

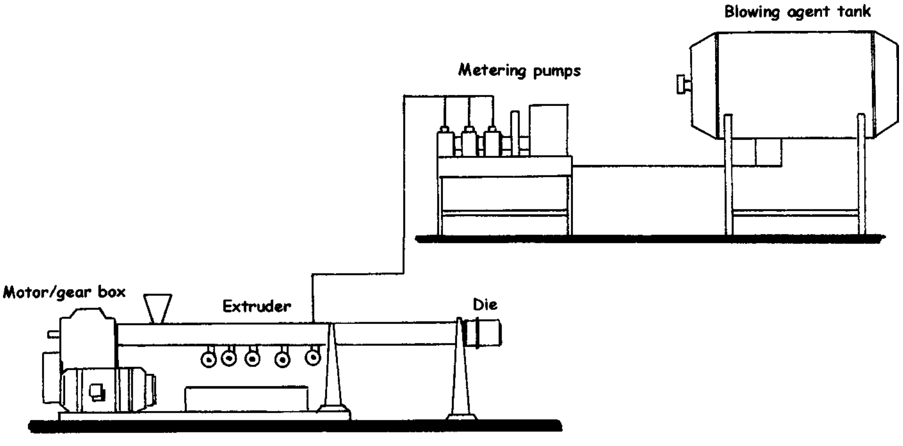

Figure 5.17 *Foaming agent platform, with foaming agent tank and metering pumps*