mixing devices becomes more apparent as the mixing requirement becomes more difficult. For example, when lower amounts of additives are to be blended into a base material, the mixing requirements are tougher. Also, when the blended ingredients are more dissimilar, the mixing chore is harder to accomplish. A system that uses an injection technique along the barrel to add ingredients can present complications because the length of screw to accomplish the mixing is shortened, as compared to blending in the extruder feed hopper, and the additives (sometimes liquids) can disrupt the screw's melting and pumping functions, also adding to homogeneity problems.

Devolatilizing (Venting)

Some materials will produce a melt that becomes porous as it exits the conventional extruder, for several reasons. Usually this phenomenon is unacceptable except where a foamed product is desired. The porosity can be caused by moisture that has been absorbed by the material, or collected on its surface, which expands into steam as the hot melted material exits the extruder and drops to atmospheric pressure. The material enclosed in the extruder and die system is usually under sufficient pressure to keep the moisture in the melt and not expanded. Other causes for porosity in the melt may include trapped air (typical of powder materials) and certain volatiles, which escape from the material and expand at atmospheric pressures. Depending upon the cause of the porosity, the approach to eliminating the bubbles can be varied. Placing an opening (vent) through the extruder barrel wall is the typical method to remove volatiles before they can reach the die system. Use of a vented extruder requires that the material in the screw flights be at atmospheric pressure (partially empty flights) under the vent opening to keep material from flowing out of the vent opening and defeating the degassing function by blocking the escape path for the volatiles. The open vent hole is fitted with an insert (vent stack) that aids in streamlining the material's flow as it passes the barrel opening, to prevent material from getting caught on any blunt edges, which would lead to a blocked opening and cause venting problems. This requirement complicates screw efficiency and leads to long extruder barrel lengths in most cases (30 : 1, 34 : 1, up to 40 : 1 extruder L/D).

There are sometimes ways to avoid venting through the extruder barrel, depending upon the cause of the porosity. Trapping air with powder feed materials can be avoided by using pelletized materials instead of the powders, or by using a vacuum on an enclosed hopper system to remove the air before it becomes trapped in the early part of the screw. The pellet approach adds the expense of an additional extrusion operation but is sometimes the more efficient choice versus the venting approach. The vacuum hopper method includes some difficulties, such as the need to load the hopper—which is now a closed system—under vacuum. Also, there are seals on the screw shank at the rear of the feed section that must be maintained or air will be drawn into the feed throat (along the screw shank), and feeding will be disrupted as this air "bubbles" up through the feed throat. Air removal utilizing an extruder vent system usually can be accomplished by a simple open vent hole, but removal of moisture and most volatiles requires having a vent vacuum system to aid in boiling off the trapped gas. Moisture can be removed through the use of desiccant drying systems, which can operate in the extruder hopper or in a remote unit. Some materials that absorb moisture from the atmosphere (are hygroscopic) must be dried even if venting is chosen, to avoid foaming at the vent opening, which blocks the volatile's escape and defeats venting. The level of moisture in the material entering the extruder thus must be reduced to allow proper and continuous venting with some highly hygroscopic materials. The choice of the method to prevent porosity is driven by the processing difficulties of the available choices versus the economics of materials and/or production methods.

Effects of Extruder Accessories

Melt Pumps. Melt pumps attach to the exit end of an extruder and are made up of two intermeshing gears that are driven. (See Fig.

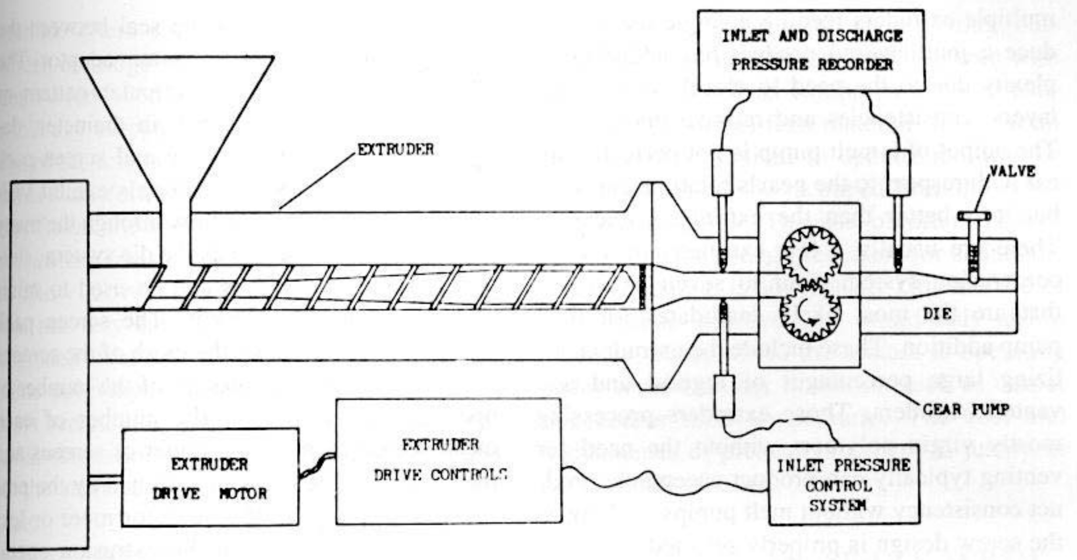

Fig. 4-5. Extrusion line with melt pump. (*Courtesy Davis-Standard*)

4-5.) The melt from the extruder enters the gear mesh and is pumped into the die system with very accurate flow consistency. Typically, the pressure on the extruder side of the gears (suction pressure) is lower than the exit pressure (die system pressure), with the gears developing the pressure rise. The gear pump thus can reduce the pressure required at the end of the extruder dramatically, a most important effect in vented extrusion. These devices have been on the extrusion scene for many years but have only recently found increased favor in general extrusion systems.

There are many published reports on the benefits of the use of melt pumps on the ends of extruders. Many of these claims are very dependent upon operational specifics (polymer material viscosities, die pressures, etc.), but the principal strength of a melt pump is its ability to ensure extrusion output consistency (pumping stability) where the screw design cannot.

Most single stage (nonvented) screw designs using today's technology can ensure excellent output stability and thus make economic justification of the melt pump very questionable. However, in some cases even a good screw design's ability to ensure stability is problematic, as with varying feed densities when there is random regrind addition to the main feed material. These cases sometimes can be shown to benefit from a melt pump. Some products demand ultimate precision in their final dimensions, which may also justify use of a melt pump if the screw cannot be proved to process the material with the required stability. An obvious application for melt pumps is with vented extruders, where the screws cannot be designed with the versatility or excellent output stability of nonvented designs; then the melt pump can restore stability to the extrusion system. The vented screw design also is limited by die pressure, which must be overcome to maintain an open vent; so the melt pump's ability to remove much of the pressure from the screw is a major advantage. There are limitations to the pressure differential across the gear mesh; very high die pressure applications (5000 psi and greater) should be carefully evaluated with the melt pump supplier.

The fiber industry has used melt pumps for years to split the melt stream of a large extruder into multiple paths that each have a pump. This setup allows consistent flow into the separate die systems, which each require only a small percentage of the extruder's output. The alternative to this system is to use many small extruders to fill each small die system individually, which would be much less efficient and prohibitive in cost, with added operational difficulties.

Coextrusion system users have shown added interest in and use of melt pumps. The use of multiple extruders feeding a single die to produce a multilayered product has added complexity due to the need to closely control the layers' consistencies and relative thicknesses. The output of a melt pump is not perfectly linear with respect to the gear's rotational speeds, but it is better than the extruder's linearity. There are usually a few extruders in a large coextrusion system (four to seven extruders) that are the most likely candidates for melt pump addition. These include the extruders utilizing large percentages of regrind and any vented extruders. Those extruders processing mostly virgin polymers without the need for venting typically can product acceptable product consistency without melt pumps, as long as the screw design is properly selected.

Melt Filters. There typically is a filtration of the melt after it exits the extruder barrel to trap any contaminants or impurities before they enter the die system. Large contaminants that enter the extruder with the material by mistake can be damaging to dies, melt pumps, and so on; so they are best caught at the end of the extruder. Many extruders are equipped with a tramp metal removal system in the feed throat to catch the most destructive contaminants before they reach the screw because the screw and barrel also can be damaged by metal pieces. These metal systems usually are magnets to catch the carbon steel pieces, which are most typical; but other systems are available that detect and remove all metals as the material drops through the feed throat.

The simplest melt filter is a screen pack held at the end of the extruder barrel by a perforated disc called a breaker plate. (See Fig. 4-6.) The breaker plate also forms the seal between the extruder barrel and the die system adaptor. The breaker plate can have a circular pattern of holes from $\frac{1}{8}$ inch to $\frac{3}{8}$ inch in diameter, depending on the extruder size and screen pack support required. Some materials exhibit visible streaks caused by the flow through the many holes as the extrudate exits the die system; slotted openings sometimes can be used to minimize this quality deterrent. The screen pack typically is specified by the mesh of the screens selected (which is a measure of the number of openings per inch) and the number of each mesh screen used. The number of screens and their restrictiveness are determined by the production operators as the need for more or less filtering is realized from the extrusion operation, usually based on melt quality requirements. A modest screen pack would be defined as having one 14 mesh, one 40 mesh and one 60 mesh screen. A fairly restrictive screen pack, as may be used with some low viscosity flexible vinyl applications, would include these screens: one 14 mesh (placed first against the breaker plate), one 40 mesh, one 60 mesh, one 120 mesh, two 200 mesh, and one 14 mesh (placed nearest the end of the screw). The coarse 14 mesh screen placed after the tight 200 mesh screens helps hold the fine screens in place as the breaker plate is being installed and the extruder is started up. The normal approach to screen pack selection is to choose the minimum screen pack to perform the job. The tighter the screen pack restriction, the sooner the pack will become plugged with contaminants.

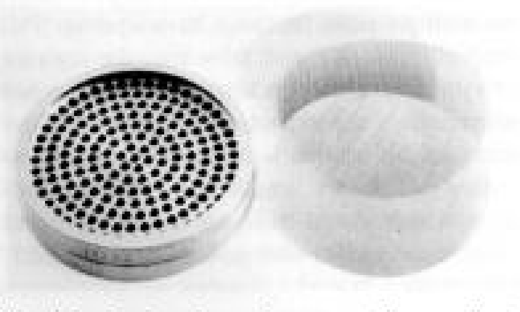

Fig. 4-6. Breaker plate and screens. *(Courtesy Davis-Standard)*

When the pressure at the screw tip reaches a designated level above that of a clean and nonrestrictive screen pack, the extruder is stopped, and the breaker plate is removed for screen replacement. Should the extrusion line be difficult to tear down to gain access to the breaker plate, an automatic screen changer can be installed; this allows removal of the breaker plate via a sliding mechanism with a replacement moving into place as the plugged screen pack is being moved out, affording minimum down time. Some systems can remain running as the change is made. These screen changers can be supplied for manual or hydraulic powered operation. There are also systems that utilize a screen cartridge in a roll which can be continuously fed over a stationary breaker plate to avoid any stoppage difficulties. Seals at either end of the screen strip passing through the melt stream are formed by small cooling passages that freeze the melt. As the screen is moved, the sealing areas are allowed to heat up enough to allow movement of the screens. Materials that are very sensitive to heat and are easily degraded over short periods of time (such as some polyvinyl chlorides) cause concern with most screen changers due to the areas of material stagnation around the breaker plate and in the melt sealing regions around the slide plate.

When a very fine filtration is desired, as with some very low viscosity melts, a canister-type filter is utilized. This type of device can filter particles at least down to 100 to 200 microns in size. The need for this type of filtration is rare in the vast majority of extrusion applications.

Material Driers or Preheaters. Materials that are hygroscopic (e.g., acrylics, polycarbonates, ABS, nylons, polyesters, etc.) typically are predried before extrusion, even when barrel vents are used to remove volatiles. Driers are usually of the desiccant type; air is heated and circulated through desiccant beds where its moisture level is reduced before traveling through the plastic in the hopper. These driers can be mounted directly on the extruder as long as adequate volume is provided to allow the desired drying residence time. Some driers have moisture level indication because there are cases where the moisture level in the material must be held quite low, such as for polyester, where the material's properties are reduced if moisture is present in even small quantities. Some materials require moisture levels to be reduced to the 0.01% range in the drier, which is within the capacity of today's desiccant units. The air temperature must be kept below the softening point of the material to avoid premelting, bridging, or sticking.

This drying situation preheats the material and increases the output rate of the extruder. The energy imparted before extrusion reduces the amount of energy required for melting; output gains of 10 to 20% typically are seen with preheated material as compared to room temperature (or colder) feed material. Some or all of the energy required to operate the drier or for preheating can be recouped from the extrusion output gains. The use of driers is well known, but the use of preheaters for enhancing extrusion output is not typical. This method of performance improvement would only aid in extrusion cases where the system is operating under some extruder limitation such as output rate and/or melt temperature. The cost and maintenance of preheaters is hard to justify in the majority of cases.

TWIN SCREW VS. SINGLE SCREW OPERATION

This discussion is centered on single screw extruders, but a brief discussion of twin screw extruders may help the reader to achieve a fuller understanding of the equipment used in the industry to process polymers. Twin screw extruders (or more-than-one-screw extruders) have multiple screws within the same barrel that may have fully intermeshing, partially intermeshing, or totally nonintermeshing flights. The screws can rotate in the same direction (co-rotating) or opposite to each other (counter-rotating).

The use of twin screw extruders to form most thermoplastic materials into final products (film, profiles, wire coatings, etc.) typically is not economically justifiable compared with the simpler single screw extruder. Single screw machines continue to greatly outnumber the multiscrew machines in general extruder sales volume, but compounding applications usually use twin screws for their dispersive mixing ability; twin screws also are favored for rigid PVC powder applications because of their low shear processing and venting capabilities.

Co-rotating screws (intermeshing or not) are primarily used for compounding and mixing, because of their ability to disperse additives of very small particle size (e.g., carbon black agglomerates). Counter-rotating and fully intermeshing flight extruders are used primarily for the low-shear extrusion of rigid PVC into pipe and profiles, typically from powder feed. This setup creates the lowest-shear extrusion situation.

The most numerous multiscrew extruders presently in operation are, by far, the twin screw type. The screw O.D.'s may be constant, as in single screw extruders, or conical, where the feed end of the screw has a larger diameter than the exit end. The conical design allows for more feeding area for powder entry to the screw and reduces the thrust due to die pressure at the smaller screw tip. The conical twin screw is used mostly for rigid PVC powder extrusion at rates up to 700 to 1000 pounds/hour. Above those output rates, a parallel twin screw is used. The twins used in profile and pipe extrusion are almost exclusively for processing rigid PVC powder, because of the low-shear fusing characteristics of this unique material and the need for venting to remove trapped air. The die pressures encountered in profile extrusion (3000–7000 psi) are difficult to handle on single screw equipment, whereas the fully intermeshing twin screw creates enough pumping efficiency to allow an open vent situation at moderate to high output rates.

High output compounding applications, where various materials are mixed in the extruder and formed into pellets for subsequent product extrusion, often are performed with large twin screw machines. This application requires very high output rates (3000–20,000+ pounds/hour), probably has a venting requirement, and does not need to deliver a melt with high product quality in terms of surface smoothness, output consistency, final material properties, and so on. Twin screw extruders with special dispersive mixing sections are typical in these compounding operations, with very large costs involved. (See Fig. 4-7.)

SINGLE SCREW EXTRUDER PHYSICAL DESCRIPTION

Barrels

The extruder barrel not only houses the screw, but serves as the primary heat transfer medium in the process. It must be designed to resist wear, contain the process pressures, and oppose screw torque. (See Fig. 4-8 for cutaway view of an extruder.)

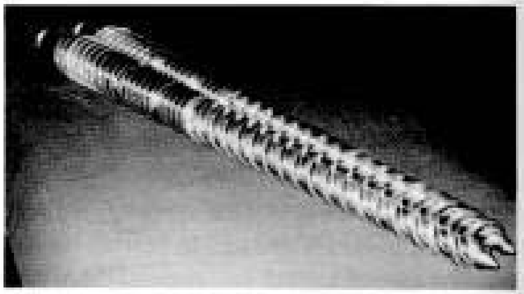

Fig. 4-7. Conical twin screws. (*Courtesy Davis-Standard*)

Materials of Construction. Barrels normally are steel cylinders with a flange at the feed end for mounting to the machine and another at the discharge end for mounting the die system. The flanges are threaded on or welded. Alloy steel typically is used because of its strength, high-temperature performance, and economy.

Liner Materials for Wear Resistance. Nitrided barrels were once common in the United States and still are used frequently in Europe. They offer moderate wear life for a reasonable cost, but the hard surface is very thin, and once it is penetrated, wear progresses rapidly. Most extruders now have a cast-in bimetallic liner that provides superior wear resistance at a moderate cost and lasts two or three times as long as nitrided barrels. General-purpose liner alloys are iron-based and are adequate for most applications. Nickel-based alloys are available for highly corrosive materials, and alloy matrixes containing tungsten and other carbides can be supplied for extreme wear and abrasive conditions.

Barrel Strength. An extruder barrel must be designed to withstand the internal pressures generated in the process. The industry standard is a design limit of 10,000 psi (70 MPa), but one should always confirm an individual machine's limit before operating at high pressures. Under normal circumstances, an outside diameter of 1.5 to 2 times the inside barrel diameter is necessary.

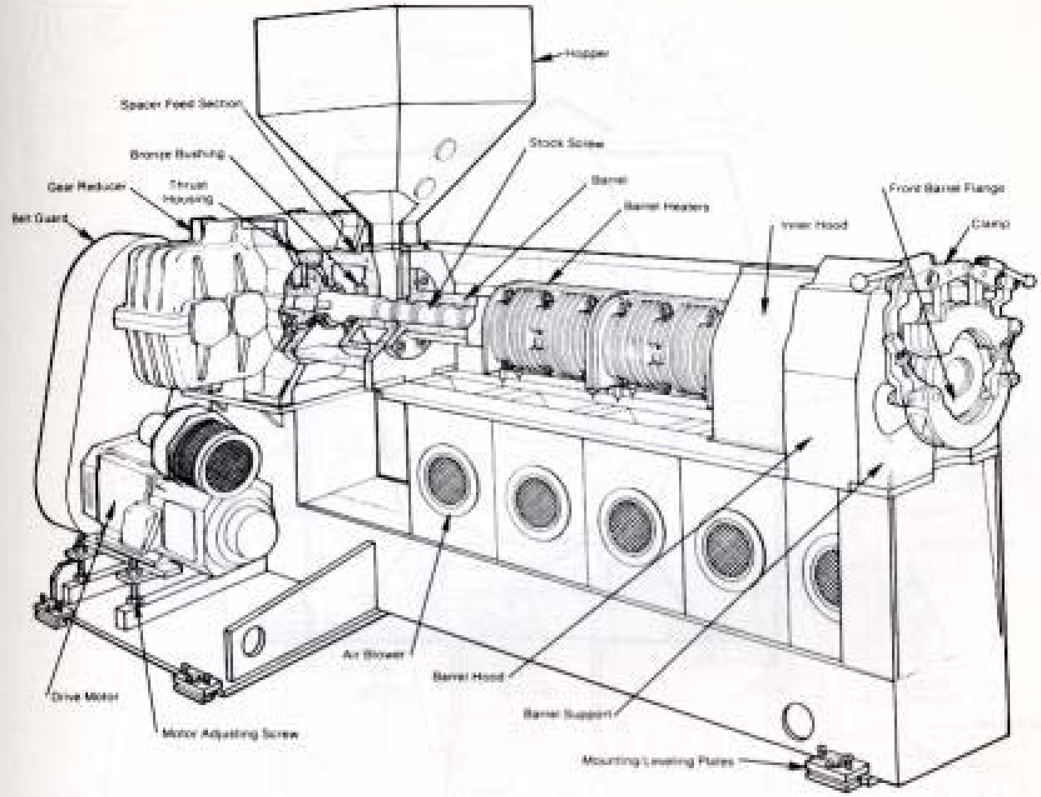

Fig. 4-8. Cutaway view of extruder. (*Courtesy Davis-Standard*)

Heating/Cooling Systems

Extruder barrel heating and cooling is necessary both for the addition and removal of heat and for the maintenance of the desired inner barrel surface temperature. The heating/cooling design must provide the required quantity of heat management as well as controllability. A typical extruder barrel is divided into control zones, each of which can be individually controlled to a desired setpoint.

Heating Designs. Many different heater designs have been used for barrel heating although, presently, electrical resistance heaters are used almost exclusively throughout the extrusion industry. Mica, ceramic, and other forms of strapped-on band heaters are common and economical, and are found on many low-cost and small-size extruders, but they suffer from poor life and performance. Cast aluminum heaters with electrical elements integrally cast inside now are accepted as the best design and are found on most modern extruders. These heaters are machine-bored in matched halves to fit closely to the barrel outside diameter when bolted or strapped on. The aluminum acts to eliminate temperature differentials and "hot spots" within the heater, gives excellent conduction to the barrel if properly mounted, and generally provides long service life.

Air Cooling. Air is an obvious choice for barrel cooling due to its simplicity, cleanliness, and economy. Air cooling can range from nothing more than convection for low-demand applications to forced air blower designs for more demanding processes. (See Fig. 4-9.) Inefficiencies in heating designs can be compensated for fairly easily by increased power levels, but air cooling designs, which must work with the available ambient air, are much

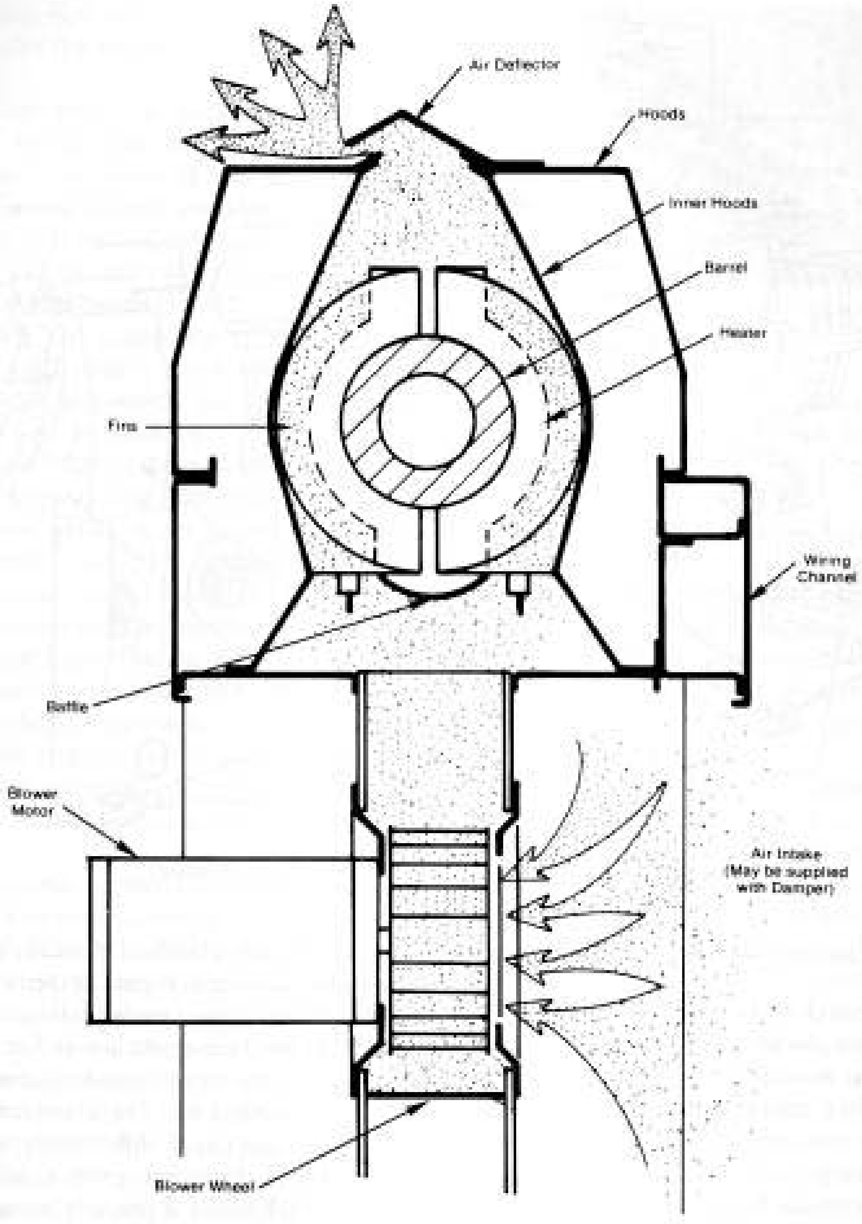

Fig. 4-9. Air flow diagram. (*Courtesy Davis-Standard*)

less tolerant than heating designs. Finned cast aluminum designs offer the best cooling efficiency, especially when properly ducted and supplied with high capacity blowers. Fins drastically increase the surface area exposed to the flow of air, the limiting factor for cooling efficiency. Sophisticated designs compensate for the cooler air at the entrance by increasing velocity at the exit. The better air-cooled designs can accommodate most extrusion processes.

Water Cooling. Water cooling provides for the sizable heat removal demand of high-load processes, offering as much as twice the efficiency of air cooling. (See Fig. 4-10.) Modern water-cooled extruders are usually equipped with cast aluminum heaters that include cast-in cooling tubes of stainless steel or Incoloy. Older designs utilized swaged-in tubing in a spiral groove on the barrel's outer diameter, over which band heaters were mounted, but these designs were plagued with poor heat

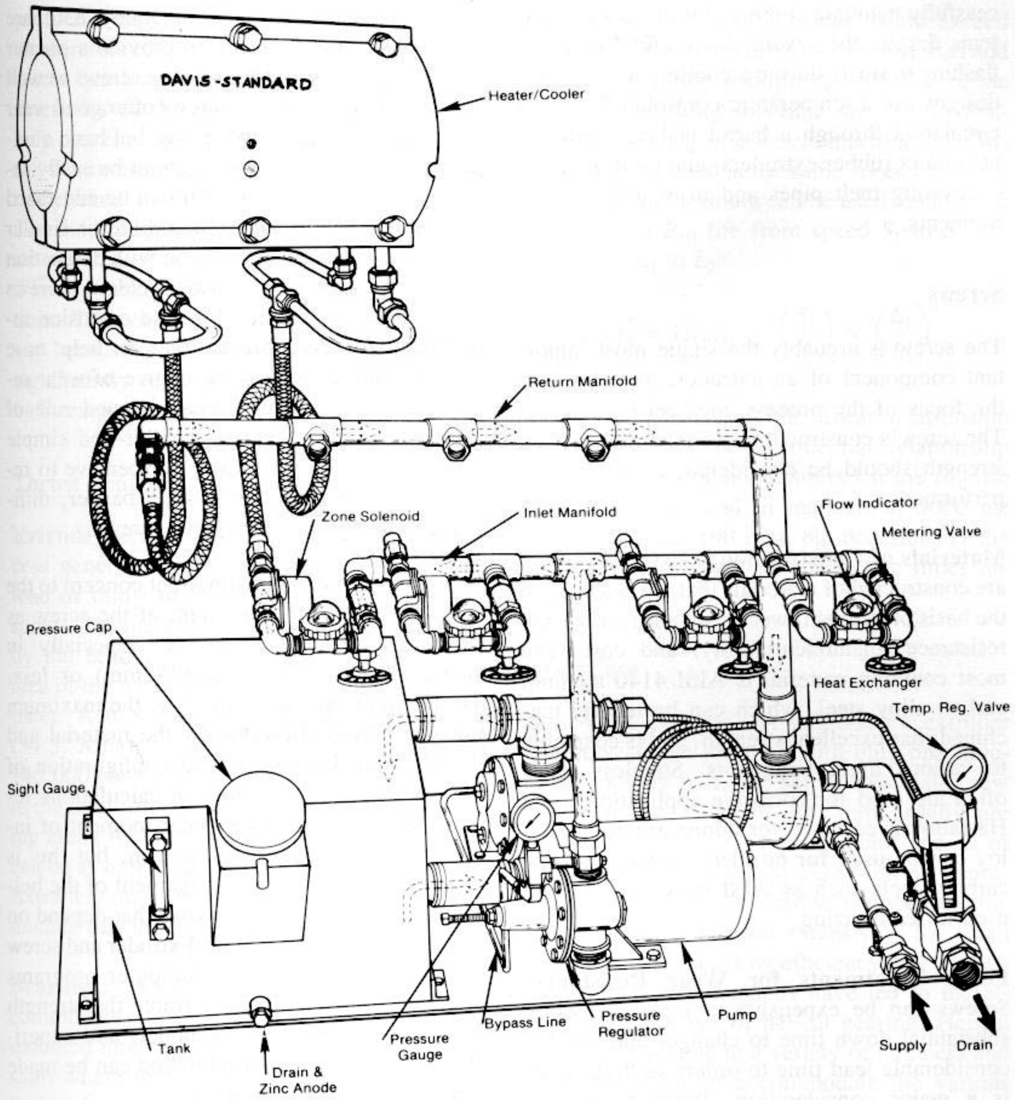

Fig. 4-10. Closed loop cooling system. (*Courtesy Davis-Standard*)

transfer and maintenance problems. Water cooling efficiency depends upon the total surface area or length of the cooling tube and on water velocity. High-temperature processes require sophisticated controls to accommodate the tremendous heat removal resulting from vaporization of the cooling water.

Water-cooled extruders are usually equipped with a self-contained closed-loop water supply system so that distilled or treated water can be circulated through the heaters to avoid scale buildup. The system consists of a tank, pump, heat exchanger, and distribution manifolds. Better systems include pressure regulation, temperature regulation, flow control, and flow indication. Water cooling is modulated by activating solenoids in response to temperature controller timed outputs.

Other Cooling Systems. Oil or other heat transfer fluids sometimes are used for barrel cooling. These fluids used to be more popular for stability reasons, prior to the advent of modern temperature controls, which can successfully maintain control of water-cooled systems despite the severe shock effect of water flashing to steam during a cooling cycle. A few designs use a temperature-controlled liquid in circulation through a barrel jacket, originally utilized in rubber extruders, and used often for controlling melt pipes and in explosive environments.

Screws

The screw is arguably the single most important component of an extruder, and certainly the focus of the process engineer's attention. The screw's construction, wear resistance, and strength should be considered, as well as its performance.

Materials of Construction. Extruder screws are constructed of materials that are selected on the basis of strength, wear resistance, corrosion resistance, manufacturability, and cost. The most common material is AISI 4140 medium carbon alloy steel, which can be readily machined, has excellent strength, and is adaptable to various flight treatments. Stainless steels often are used for corrosive applications, and Hastalloy is common for fluorocarbons. Nitraloy can be used for nitrided screws, and low carbon steels such as AISI 9310 or 8620 are used for carburizing.

Flight Treatments for Wear Resistance. Screws can be expensive to replace, require substantial down time to change, and involve considerable lead time to order; so flight wear is a major consideration. Wear contributes drastically to decreases in performance, quality, and productivity. Flights generally are manufactured for maximum wear by hardening, special coatings, or the welding of a hard layer on the surface. The most common configuration is flame-hardened 4140, which gives moderate life at reasonable cost, can be rebuilt when worn, and is suitable for most nonabrasive materials. Wear-resistant alloys, such as Colmonoy 56, Stellite 6, or Xaloy 830, are welded onto the flight tip to provide a greater degree of wear resistance on new screws as well as on rebuilds. Nitralloy screws offer good wear resistance at a reasonable price, but have a relatively thin case depth and cannot be easily rebuilt. Extreme cases of wear can be addressed by applications of tungsten carbide or similar coatings, which are sprayed on with detonation guns or high-velocity plasma welders. Screws often are chrome-plated for mild corrosion resistance, for rust prevention, to help ease cleanup, and to offer some degree of wear resistance in the channel area. A good rule of thumb is to flame-harden smaller and simple screws, which are easy and inexpensive to replace, and hardface larger-size, barrier, difficult-to-replace, and expensive screws.

Screw Strength. An important concern to the screw designer is the strength of the screw as it relates to torque capacity, especially in smaller sizes of 3 inches (75 mm) or less. Torque limits are determined by the maximum torsional stress allowable by the material and the physical dimensions and configuration of the screw. Strength-in-torsion calculations require computation of the polar moment of inertia of the screw's cross section; but this is difficult because of the arrangement of the helical flight, which has properties that depend on its hardness or composition. Extruder and screw manufacturers often have computer programs or calculations that can determine the strength fairly accurately based on models and experience. An adequate approximation can be made from the following formula:

$$\text{Torque} = \frac{\pi\left\{(\text{Dia.} - [\text{Channel depth} \times 2])^4 - (\text{Core dia.})^4\right\}}{16 \times \text{Dia.}} \times \text{Permissible stress}$$

This formula ignores any strength contribution of the flight, but then does not include any safety factor. If the screw is of normal proportions, the formula should prove adequate for estimations of strength.

Screw Heating and Cooling. Most screws benefit from a core at least as deep as the feed area so that bridging or compound sticking problems can be avoided by cooling. Screw temperature control of the first stage of a vented screw can help to balance the pumping characteristics of the two stages. Tip cooling can help prevent material from burning at the screw tip. Screw heating and cooling usually are accomplished through water or oil circulation. The fluid is supplied to a small-diameter coaxial tube inside the core hole and returns through a rotary union with inlet and outlet connections. Temperature control is especially important because the screw surface temperature can significantly affect the extruder flow rate and melt temperature.

Thrust Bearings

Extruder Screw Thrust. The extrusion process generates a tremendous amount of axial load or thrust directed toward the rear of the screw. The major component of thrust is caused by the head pressure acting upon the frontal area of the screw, which is like a hydraulic cylinder. A 6-inch (152 mm) screw at 5000 psi (34.5 MPa) generates thrust in excess of 140,000 pounds (620 kN). Another contributor to the total force is the pressure differential acting along the entire length of the flight, which can be as high as the head pressure component. Extruders must be designed to reliably accommodate this thrust.

Bearings. Modern extruders commonly accommodate thrust with a thrust bearing mounted integrally to the gear reducer's output shaft where the screw engages, usually of cylindrical or tapered roller design. Thrust bearings typically are long-lasting and trouble-free, but, in demanding applications of high head pressures or speeds, they require attention to their selection and, most important, to their lubrication. Adequate oil flow is necessary for bearing cooling as well as lubrication, the lack of which is the leading cause of problems and failure.

B_{10} Life Calculations and Comparisons. Extruder manufacturers normally list the thrust bearing rating in terms of a B_{10} or L_{10} life, which is the time in hours that 90% of a controlled test sample of bearings would exceed without failure at similar conditions of load and speed. This figure also implies that 10% of the bearings fail during this time. In order to compare the capacity of different machines, the B_{10} lives must be rated at the same speed and load. The following formula can be used to calculate the adjusted B_{10} life from speed S_1 to S_2 and from load L_1 to L_2:

$$(B_{10})_2 = (B_{10})_1 \times \left(\frac{S_1}{S_2}\right) \times \left(\frac{L_1}{L_2}\right)^{3.33}$$

The formula shows the linear relationship with speed and the exponential relationship with load. Most manufacturers list the B_{10} life in the literature and in manuals at 5000 psi (34.5 MPa) and 100 rpm, but occasionally the average life is listed—which is five times the B_{10} life.

Gear Case

Gear Case Designs. A single-screw extruder is a very simple machine with only one functional moving part, the screw. Normal screw speeds in the range of 100 rpm usually are achieved by reducing typical motor speeds of 1750 rpm through a gear case with an appropriate ratio. Worm gear reducers once were the norm and still are used extensively for small machines, but their low efficiency and today's increased power demands have led to the almost universal use of helical gearing. Helical gears are available in a variety of hardness and precision levels to accommodate the various speeds and loads found in extrusion. The gear case should always be supplied with a safety factor of 1.25 for smaller machines and 1.50 for large extruders.

Lubrication. The gear case lubrication system must provide proper lubrication for the gear meshes and, perhaps more important, the bearings. Oil supplies are used for cooling the bearings and gears, and on large machines and in demanding applications, a forced lubrication system should be employed to ensure an adequate supply to each bearing. All gear reducers have a thermal limit beyond which some sort of cooling is necessary. A heat exchanger in the oil circulation system of high load machines is the normal means for providing cooling and maintaining proper temperatures.

Power–Speed–Torque Relationships. Extruder timing involves careful consideration of several factors in order to accommodate a particular application. Timing refers to the speed at which the full motor horsepower is applied to the extruder screw. It involves the reduction ratio of the gearbox combined with the ratio of the belts and pulleys (when used) that connect the motor to the extruder. Motors are rated at full horsepower at a base speed, usually 1750 rpm. A DC motor's power output is proportional to speed; so it is rated at $\frac{1}{2}$ power at $\frac{1}{2}$ speed, and so on. An extruder timed at 75 rpm, for instance, has a total reduction ratio of 23.3:1 between a 1750 rpm motor and the screw. More important, the motor torque is multiplied 23.3 times to the screw. Torque is the quantity that best describes the force or power applied to turn the screw, and it is directly related to motor load or amps. Torque is best understood if expressed in terms of horsepower per rpm rather than as foot-pounds or inch-pounds.

Any particular extruder screw and material combination has a specific torque requirement. The drive initially is timed at a speed that provides the best compromise between torque available to the process and speed required. A processor who tries to run a new material on an extruder and experiences high motor loads actually is experiencing high torque demands. The torque (hp/rpm) available to the process can be increased either by increasing horsepower or by decreasing the timing (maximum screw speed). Belt drives are used on most extruders so that the timing can be changed easily by changing the pulley reduction ratio. Similarly, when higher speeds are required, and motor load is low, the extruder can be timed higher by changing pulleys—but one should be aware that this also reduces the available torque.

In changing timing, the gearbox capacity must always be considered. Gears have a torque limit that restricts the low end of the timing range and sometimes a thermal capacity that limits the upper end. One should always check the gear rating nameplate or consult with the manufacturer before retiming an extruder.

Drive Motor

The drive motor provides power for the conveying, melting, and pumping processes and establishes extruder output by maintaining a desired speed. DC electric motors are by far the most popular drive type because of their economy, serviceability, and accuracy. A DC drive is a constant torque device, which meets most processing requirements quite well and matches the capabilities of a typical helical gear case. AC variable frequency drives are gaining in popularity as their cost comes down but offer little advantage for most extrusion applications. Hydraulic drives are seen in some machines, but are much more complex and costly than the typical DC drive; and even though they allow for the elimination of the gear case, they offer no advantage in most applications.

Drive Coupling

The drive motor can be connected to the gear case directly by a coupling or by an arrangement of pulleys and belts. Direct coupling is necessary in large machines over 300 hp (225 kW); but it requires precision motor alignment and a specific gear ratio for each application. Belts and pulleys, the better system for smaller machines, are much more flexible as far as timing changes are concerned and give many motor mounting options. Modern designs operate with very little maintenance and high efficiency.

EXTRUSION CONTROLS AND INSTRUMENTATION

Basic Control Requirements

Extruders require some level of control of basic functions and can benefit from enhanced control of other functions. Minimum requirements include some form of barrel temperature control, drive speed control, and drive load indication. Head, or breaker plate, pressure indication also is typically included in the most basic systems. The demands of modern manufacturing methods, quality issues, and process control have dictated much more extensive control systems and instrumentation on many of today's extrusion lines. Extrusion controls have benefited from the overall rapid technology growth in the electronics, controls, computer, and instrumentation industries.

Sensors and Monitors

Barrel Temperature Measurement. Barrel temperature control is one of the most critical functions, so temperature sensing is extremely important. A sensor typically is located in the center of each barrel zone, traditionally at the bottom. Extruder barrels have substantially thick walls in order to withstand internal pressures, but the critical control surface is at the inside. The ideal sensor would be mounted at the inside surface, but this is generally impractical; so a deep hole normally is drilled to within $\frac{1}{8}$ inch or less of the inside, usually against the hard barrel lining. Thermocouples are the most commonly used sensor because of their durability, simplicity, and accuracy. Thermocouples also are the most accurate and best-suited sensor for the application because they sense the temperature at their tip, which is in contact with the bottom of the drilled hole and very close to the control surface. RTDs (Resistive Temperature Detectors), are often specified in sophisticated control systems, and as a sensor, are more accurate; but they are not well suited to this application because of the length of their sensing element, which measures a temperature some distance from the desired inner surface. The most advanced barrel control systems use a second thermocouple in the heater as part of their control scheme.

Melt Temperature Measurement. The polymer melt temperature often is a limiting parameter in the process, so its accurate measurement is extremely important to the serious processor. Measurements typically are made by utilizing a melt thermocouple installed in a hole that exposes the sensor directly to the polymer. Production lines often use flush designs, combination pressure transducer/thermocouples, or probes with only a small projection into the melt stream because these designs are fairly durable. Conduction effects from the die body and the relative slow velocity layer of melt near the wall may render these sensors ineffective, however.* Accurate melt temperature measurement requires a thermocouple, ideally extended into the center of the flow channel but at least $\frac{1}{2}$ inch into the stream; for maximum accuracy, an exposed-junction low-mass thermocouple is used. Fiber-optic infrared probes recently have been developed, but because of limited optical penetration into the melt they also must be mounted on a protruding probe. Adjustable-depth probes, either manual or automated, allow for optimum positioning but provide for retraction to protect the element during cleaning and start-up.

Pressure Measurement. Pressure measurement is of critical importance to the extrusion process as a window into the operation. Early designs utilized a high-temperature grease in a tube connecting a hole in the barrel to a Bourdon tube type mechanical gauge, but were plagued with maintenance and durability problems. Modern gauges all use a diaphragm that isolates the hot polymer from the sensing device and either directly actuates a mechanical gauge or utilizes a strain gauge transducer. Two basic concepts dominate the industry: push rod types, which mechanically connect the diaphragm to the gauge or transducer, and liquid (usually mercury)-filled capillary types, which transmit pressure hydraulically from the diaphragm. The push rod has the reputation of being more durable and less costly, whereas the capillary type is generally thought of as more accurate and much less temperature-sensitive. These reputations are well deserved, but recent designs have resulted in improvements in both types.

At a minimum, extruders should have one pressure transducer located before the breaker

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*See E. L. Steward, "Making the Most of Melt Temperature Measurement," *Plastics Engineering*, Society of Plastics Engineers, July 1985.