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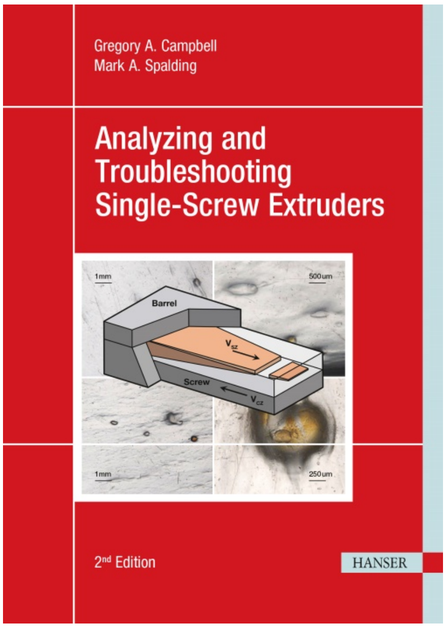


# Sample Pages

# Analyzing and Troubleshooting Single-Screw Extruders

Gregory A. Campbell and Mark A. Spalding

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# Preface

Classically, all prior extrusion books are based on barrel rotation physics. Literature developed over the past 15 years has led to this first book to be published based on the actual physics of the process—screw rotation physics. After the theories and the math models are developed in the first nine chapters, the models are then used to solve actual commercial problems in the remainder of the book. Realistic case studies are unique in that they describe the problem as viewed by the plant engineers and provide the actual dimensions of the screws. Knowledge is developed using a series of hypotheses that are developed and then tested, which allows a series of technical solutions. Several actual solutions are proposed with the final results that solve the problem then clearly presented. Overall, there is not a book on the market with this level of detail and disclosure. New knowledge in this book will be highly useful for production engineers, technical service engineers working with customers, consultants specializing in troubleshooting and process design, and process researchers and designers that are responsible for processes that run at maximum rates and maximum profitability.

Debugging and troubleshooting single-screw extruders is an important skill set for plant engineers since all machines will eventually have a deterioration in their performance or a catastrophic failure. Original design performance must be restored as quickly as possible to mitigate production losses. With troubleshooting knowledge and a fundamental understanding of the process, the performance of the extruder can be restored in a relatively short time, minimizing the economic loss to the plant. Common root causes and their detection are provided. Hypothesis testing is outlined in Chapter 10 and is used throughout the troubleshooting chapters to identify the root causes. Elimination of the root cause is provided by offering the equipment owner several technical solutions, allowing the owner to choose the level of risk associated with the process modification. Mechanical failures are also common with single-screw extruders, and the common problems are identified. Illustrations are provided with the problems along with many numerical simulations of the case studies. Collectively, these instruct the reader on how to determine and solve many common extrusion problems. About 100 case studies and defects are identified in the book with acceptable technical solutions. Lastly, we hope that this book provides the information and technology that is required for the understanding, operation, and troubleshooting of single-screw extruders.

We have focused on two things as we developed the second edition of this treatise on single-screw fundamentals and application of those fundamentals to the engineering art of troubleshooting, research/development, and production single screw extruders. The stoichiometry of several important chemical reactions relating to the number of important commercial polymer monomers and their polymers was addressed in Chapter 2. Also, in Chapter 2 a table of 10 commercial polymers and their properties and structure was added so the reader can relate to some important polymers finished properties after extrusion. With the constraint of few new monomers and the cost and risk of building new monomer and polymer plants, the polymer industry has been focusing on developing rigid and fiber-based composite materials. A major addition to Chapter 3 is the development of an energy-based model for the shear thinning power law. The technique of using this new concept on polymer particulate composites is then developed and the utility of this concept is applied to the limiting extrusion-injection rate for injection molding. The difficulties of extruding a sound-deadening composite due to a filler change is related to the importance of understanding that filled system rheology is dependent on the volume and not the weight fraction of the filler. Other additions include an expansion of the design of Maddock mixers, transfer line designs, economic evaluations, and new case studies.

*Gregory A. Campbell*

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# 1 Single-Screw Extrusion: Introduction and Troubleshooting

This book was written to provide the extrusion process engineer with a resource for assessing and fixing process problems associated with the use of single-screw extruders. The authors have drawn on their complementary backgrounds; both have worked with industrial extruder design, analysis, and fundamental research in the mechanism, operation, and troubleshooting of the single-screw extrusion process. The use of single-screw extruders in production processes has progressed significantly over the past several decades. As a result, the number of single-screw extruders in use has increased dramatically as has the diameter and length of the machine, especially for melt-fed extruders used in large resin production plants. In addition, resin manufacturers have developed many new resins for final products such as extruded sheet, film, pipe, fibers, coatings, and profiles. The extruder is still the process unit of choice for producing pellets in the production of polymer materials. Two types of extruders are generally used in polymer production: single-screw extruders and twin-screw extruders. The material in this book will be confined to the analysis and troubleshooting of single-screw extruders. The rapid expansion of this part of the polymer industry has been accompanied by the need for many new extrusion engineers. Many of these engineers have not had formal training in the analysis of the extruder and screw design nor have they had extensive education in polymer materials, which would help in troubleshooting problems on production equipment.

All single-screw extruders have several common characteristics, as shown in Figure 1.1 and Figure 1.2. The main sections of the extruder include the barrel, a screw that fits inside the barrel, a motor-drive system for rotating the screw, and a control system for the barrel heaters and motor speed. Many innovations on the construction of these components have been developed by machine suppliers over the years. A hopper is attached to the barrel at the entrance end of the screw and the resin is either gravity-fed (flood-fed) into the feed section of the screw or metered (starve-fed) through the hopper to the screw flights. The resin can be in either a solid particle form or molten. If the resin feedstock is in the solid form, typically pellets (or powders), the extruder screw must first convey the pellets away from the feed opening, melt the resin, and then pump and pressurize it for a downstream process operation. This type of machine is referred to as a plasticating single-screw extruder. The barrel is usually heated with a minimum of three temperature zones. These different temperature zones are consistent with the three utilitarian functions of the screw: solids conveying, melting, and pumping or metering of the polymer.


**Figure 1.1** Photograph of a highly instrumented 63.5 mm diameter extruder built by American Kuhne

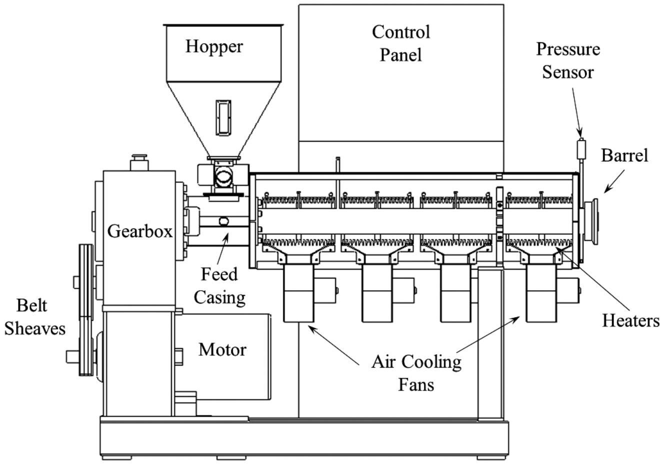


**Figure 1.2** Schematic of a typical plasticating single-screw extruder. The extruder is equipped with four barrel heating and cooling zones and a combination belt sheave gearbox speed reduction drivetrain (courtesy of William Kramer of American Kuhne)

The single-screw plasticating process starts with the mixing of the feedstock materials. Typically, several different feedstocks are added to the hopper, such as fresh resin pellets, recycle material, additives, and a color concentrate. The recycle material typically comes from the grinding of edge trim, web material from thermoforming processes, or off-specification film and sheet. Often these components need to be dried and blended prior to adding them to the hopper. Next, the feedstock flows via gravity from the hopper through the feed throat of the feed casing and into the solids-conveying section of the screw. Typically this feed casing is cooled using water. The feed section of the screw is typically designed with a constant depth and is about 4 to 8 barrel diameters in axial length. Directly after the solids-conveying section is a section where the channel depth tapers to a shallow depth-metering section. The tapered-depth section is commonly referred to as the transition or melting section. In general, the metering section is also a constant depth, but many variations exist where the channels oscillate in depth. The metering section pumps and pressurizes the material for the downstream unit operations, including static mixers, screen filtering devices, gear pumps, secondary extruders, and dies. The total length of the extruder screw and barrel is typically measured in barrel diameters or as a length-to-diameter (L/D) ratio. Section lengths are often specified in barrel diameters or simply diameters.

The plasticator on an injection-molding machine is a specialized plasticating single-screw extruder. The plasticator has two main differences: there is a nonreturn valve on the tip of the screw, and the screw retracts as molten material accumulates between the nonreturn valve and the end of the barrel. Pressure is maintained on the accumulated material by a constant force applied to the shank of the screw via the drive system. This force is typically measured as a pressure applied to the shank and is referred to as the "back pressure." During the injection step of the process, the screw is forced forward, the nonreturn valve closes, and the material is injected into the mold. Additional information on the injection-molding process can be obtained elsewhere [1].

## 1.1 Organization of this Book

This book has been organized so that the information is helpful in troubleshooting extruders and extrusion processes, and it is presented in a manner that is of maximum utility to extrusion engineers. Appendices have been provided that present the theoretical analysis and assumptions in developing the design equations used throughout this text. In order to assess extruder production problems, it is necessary to understand the nature of the polymer that is being extruded, the design of the extruder and screw, and the interaction of these as the extruder is being operated. Numerous case studies are presented that demonstrate these interactions.

Knowledge of the geometry and mathematical description of a screw is required to understand the analysis of the functional sections of the screw and the troubleshooting of case studies. In Chapter 1 the geometry and mathematical descriptions are presented. Also in this chapter, the calculation of the rotational flow (also known as drag flow) and pressure flow rates for a metering channel is introduced. Simple calculation problems are presented and solved so that the reader can understand the value of the calculations.

Resin manufacturers go to extreme measures to produce a reproducible, high-quality, and useful polymer that is ready for final conversion to a product. Every time these polymers are passed through an extruder, however, the polymer has the potential to degrade, changing the chemical and physical properties of the resin. Degradation processes can often be the cause of extrusion problems. Chapter 2 begins with an introduction to how polymers are produced from the perspective of the type of chemical bonds that are important in different polymer families. It is beyond the scope of this book to discuss polymer production processes in detail. The discussion of polymerization is intended to aid the reader with a basic understanding on how the polymer is formed from its monomer. Knowing how the polymer was produced from its monomers will provide the engineer with the knowledge of how the extrusion process interacts with the polymer. This basic understanding will help in troubleshooting situations where the problem is the effect of the extrusion process on the stability of the polymer being extruded.

The physical properties that are important to polymer processing are presented in Chapters 3 and 4. Chapter 3 provides a basic understanding of the viscoelastic characteristics of polymers. In this chapter the fundamental concepts of polymer rheology are developed, and then there is a discussion of Newtonian and Power Law rheological responses of polymeric fluids, followed by a short introduction to the elastic nature of polymer melts. Chapter 4 presents the remaining physical properties, including friction coefficients (or stress at an interface), densities, melting fluxes, and thermal properties. These properties impact the performance of a resin during the extrusion process.

The fundamental processes and mechanisms that control single-screw extrusion are presented in Chapters 5 through 8. These processes include solids conveying, melting, polymer fluid flow, and mixing. The analyses presented in these chapters focus on easily utilized functions needed to assess the operation of the single-screw extruder. The derivation of these relationships will be presented in detail in the appendices for those who desire to explore the theory of extrusion in more detail.

The remaining Chapters 9 through 15 are devoted to different types of extrusion troubleshooting analyses. These chapters include presentations on scale-up techniques, general troubleshooting, screw fabrication, contamination in finished products, flow surging, and rate limitations. The chapters are presented with actual case studies of extrusion troubleshooting problems with the detailed analytical approach that was used to address these problems. As part of this troubleshooting presentation, high-performance screws and their benefits are presented. Lastly, melt-fed extruders will be discussed. Melt-fed extruders are a special class of machines that are rarely discussed in the open literature.

Appendix A1 has a listing of the polymer abbreviations used in this book.

## 1.2 Troubleshooting Extrusion Processes

All extrusion and injection-molding plastication processes will eventually operate at a performance level less than the designed level. This reduction in performance can be caused by many factors, including but not limited to control failures, a worn screw or barrel, or a process change such as processing a different resin. Moreover, an improper screw design or process operation can limit the performance of the machine and reduce the profitability of the plant. Other processes may be operating properly at the designed rate, but a higher rate may be required to meet market demands. In this case, the rate-limiting step of the process needs to be identified and a strategy developed to remove the limitation.

Troubleshooting is a process for systematically and quickly determining the root cause of the process defect. The troubleshooting process is built on a series of hypotheses, and then experiments are developed to prove or disprove a hypothesis. The ability to build a series of plausible hypotheses is directly related to the knowledge of the engineer troubleshooting the process. Our focus is on providing the knowledge for the proper operation of an extrusion process, helping determine typical root causes that decrease the performance of the machine, and offering methods of removing the root cause defect from the process.

The economic impact of a properly designed troubleshooting process can be significant, especially if the defect is causing very high scrap rates or production requirements are not being met. Returning the process to full production in a timely manner will often require subject matter experts from several disciplines or companies. An excellent example of a troubleshooting process is described next for a processing problem at the Saturn Corporation.

### 1.2.1 The Injection Molding Problem at Saturn

During the startup of Saturn Corporation's Spring Hill, Tennessee, plant in September of 1990, a serious splay problem was encountered for the injection molding of door panels from a PC/ABS resin [2]. Splay is a common term used to describe surface defects on injection-molded parts. The splay on the surface of the door panels created parts with unacceptable appearances after the painting process. The part rejection rate was higher than 25%, high enough to nearly shut down the entire plant. Teams were formed from the companies involved to determine quickly the root cause for the splay. After a detailed analysis was performed, it was determined that the plasticating screw in the injection molder was not operating properly, causing some of the resin to degrade in the channels of the screw. The splay was created by the volatile components from the degradation of the resin. A high-performance Energy Transfer (ET) screw [3] was designed and built, eliminating the splay. A detailed discussion of the troubleshooting process at Saturn is presented in Section 11.12.5.

The troubleshooting project at Saturn is an excellent example of combining strengths from different companies to diagnose and eliminate a costly defect from a process.

## 1.3 Introduction to Screw Geometry

In order to simulate an extrusion process or design a screw, the mathematical description of the screw geometry must be understood. This section provides the basic details that describe a screw and the complex mathematics that describe the channels.

The single-screw extruder screw can be single flighted or multiple flighted. A conventional single-flighted screw is shown in Figure 1.3. This screw has a single helix wound around the screw root or core. Multiple-flighted screws with two or more helixes started on the core are very common on high-performance screws and on large-diameter melt-fed machines. For example, barrier melting sections have a secondary barrier flight that is located a fraction of a turn downstream from the primary flight, creating two flow channels: a solids melting channel and a melt-conveying channel. Moreover, many high-performance screws have two or more flights in the metering section of the screw. Barrier screws and other high-performance screws will be presented in Chapter 14. Multiple flights are very common on larger-diameter extruder screws, because this creates a narrower channel for the polymer melt to flow through, leading to less pressure variation due to the rotation of the screw. In addition, the multiple flights spread the bearing forces between the flight tip and the barrel wall. Melt-fed extrusion processes will be discussed in detail in Chapter 15. The screw is rotated by the shank using either specially designed splines or by keys with rectangular cross sections. The mathematical zero position of the screw is set at the pocket where the screw helix starts. Most extruder manufacturers rotate the screw in a counterclockwise direction for viewers positioned on the shank and looking towards the tip. This rotation convention, however, is not standard.

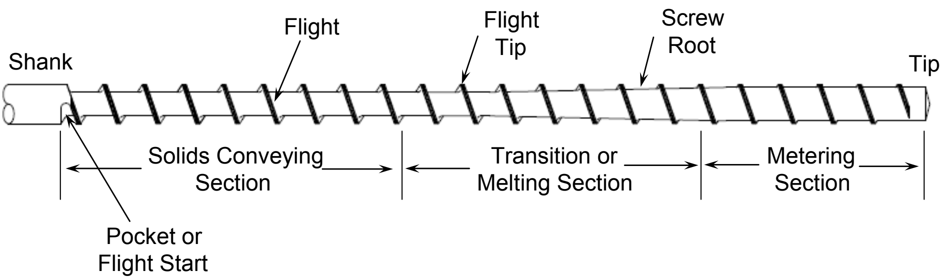


**Figure 1.3** Schematic of a typical single-flighted screw (courtesy of Jeff A. Myers of Robert Barr, Inc.)

The flight is a helical structure that is machined into the screw and extends from the flight tip to the screw core or root. The flight has a width at the flight tip called the flight land. The small clearance between the flight land and the barrel wall minimizes the flow of polymer back toward the feed section. The polymer that does flow between the clearances supports the screw and centers it in the barrel. The radial distance between the flight tip and the screw root is referred to as the local flight height or channel depth. The feed section usually has a constant-diameter core that has the smallest diameter, the largest channel depth, and the largest cross-sectional volume in the screw. The deep channel conveys the relatively low bulk density feedstock pellets into the machine. The feedstock is conveyed forward into the transition section or melting section of the screw. The transition section increases in root diameter in the downstream direction, and thus the channel depth decreases. Here, the feedstock is subjected to higher pressures and temperatures, causing the feedstock to compact and melt. As the material compacts, its bulk density can increase by a factor of nearly two or more. As the feedstock compacts, the entrained air between the pellets is forced back and out through the hopper. For example, a pellet feedstock such as ABS resin can have a bulk density at ambient conditions of 0.65 $g/cm^3$ while the melt density at 250 °C is 0.93 $g/cm^3$. Thus for every unit volume of resin that enters the extruder, about 0.3 unit volumes of air must be expelled out through the voids in the solid bed and then out through the hopper. The transition section is where most of the polymer is converted from a solid to a fluid. The fluid is then conveyed to the metering section where the resin is pumped to the discharge opening of the extruder. In general, the metering section of a conventional screw has a constant root diameter, and it has a much smaller channel depth than the feed section. The ratio of the channel depth in the feed section to the channel depth in the metering section is often referred to as the compression ratio of the screw.

### 1.3.1 Screw Geometric Quantitative Characteristics

The book *Engineering Principles of Plasticating Extrusion* by Tadmor and Klein [4] has been used extensively in gaining an understanding of the fundamentals of extrusion processes. The following section endeavors to maintain the quality of the development of the screw geometry section of this classic text. Understanding the relationships between the screw geometry and the symbolic and mathematical representation of a screw is a critical beginning for understanding the rate, pressure, and temperature calculations. These functions related to the performance of single-screw extruders are developed later in this book and require an understanding of the screw geometry.

The geometry of a double-flighted screw and its nomenclature are presented in Figure 1.4 using the classical description from Tadmor and Klein [4]. The nomenclature has been maintained to provide consistency with the classical literature and to provide some generality in the development of the symbols and equations that are used in extruder analysis.

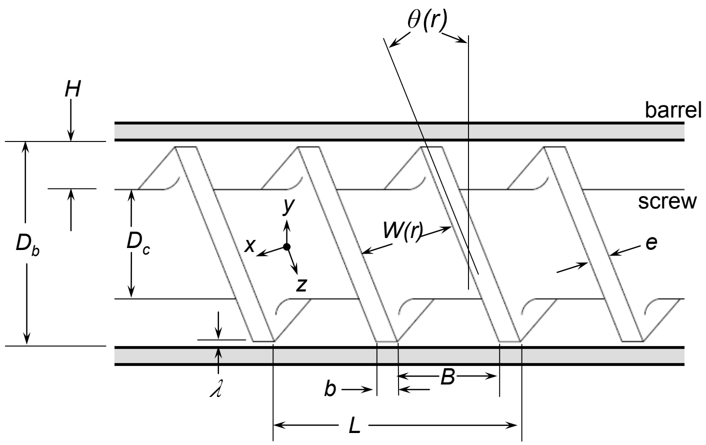


**Figure 1.4** A schematic of a double-flighted screw geometry

Several of the screw geometric parameters are easily obtained by observation and measurement, including the number of flight starts, inside barrel diameter, channel depth, lead length, flight width, and flight clearance. The number of flight starts, $p$, for the geometry in Figure 1.4 is two. The inner diameter of the barrel is represented by $D_b$, and the local distance from the screw root to the barrel is $H$. The diameter of the screw core is represented by $D_c$. The mechanical clearance between the land of the screw flight and the barrel is $\lambda$. The mechanical clearance is typically very small compared to depth of the channel. The lead length, $L$, is the axial distance of one full turn of one of the screw flight starts. This is often constant in each section of the screw, but in some screws, such as rubber screws, it often continuously decreases along the length of the screw. A screw that has a lead length that is equal to the barrel diameter is referred to as square pitched. The flight width at the tip of the screw and perpendicular to the flight edge is *e*.

The remaining geometrical parameters are easily derived from the measured parameters presented above. Several of the screw parameters are functions of the screw radius. They include the perpendicular distance from flight to flight, $W(r)$; the width of the flights in the axial direction, $b(r)$; and the helix angle, $\theta(r)$, the angle produced by the flight and a plane normal to the screw axis. These parameters will be discussed later. At the barrel wall these parameters are subscripted with a *b*. The helix angle at the barrel wall is $\theta_b$ and is calculated using Equation 1.1. The helix angle at the barrel wall for a square-pitched screw is 17.7°.

$$\tan\theta_b = \frac{L}{\pi D_b} \quad \text{thus} \quad \theta_b = \arctan\frac{L}{\pi D_b} \tag{1.1}$$

The relationship between the width of the channel perpendicular to the flight at the barrel interface, $W_b$, and the axial distance between the flight edges at the barrel interface, $B_b$, is as follows:

$$W_b = B_b\cos\theta_b = \left(\frac{L}{p} - b_b\right)\cos\theta_b = \frac{L}{p}\cos\theta_b - e \tag{1.2}$$

$$e = b_b\cos\theta_b \tag{1.3}$$

As mentioned earlier, several of the geometric parameters are a function of the radial position ($r$) of the screw. These parameters include the helix angle and the channel widths. The length of an arc for one full turn at the barrel surface is $\pi D_b$. At the screw surface the length of the arc for one turn is $\pi(D_b - 2H)$; the lead length, however, remains the same. This leads to a larger helix angle at the screw root than at the barrel surface. This analysis is for a flight width that does not change with the depth of channel. As discussed in Chapter 10, for a properly designed screw, the flight width will increase as the root of the screw is approached due to the flight radii.

The helix angle and the channel widths at the screw core or root are designated with a subscript *c*, and they are calculated as follows:

$$\tan\theta_c = \frac{L}{\pi(D_b - 2H)} = \frac{L}{\pi D_c} \quad \text{thus} \quad \theta_c = \arctan\frac{L}{\pi D_c} \tag{1.4}$$

Thus the screw has a narrower normal distance between flights at the screw root because the helix angle is larger and because the lead remains the same.

$$W_c = B_c \cos\theta_c = \left(\frac{L}{p} - b_c\right)\cos\theta_c = \frac{L}{p}\cos\theta_c - e \tag{1.5}$$

$$e = b_c \cos\theta_c \tag{1.6}$$

For a generalized set of functions in terms of the radius, $r$, and the local diameter, $D$, the helix angle is calculated as follows:

$$\theta(r) = \arctan\frac{L}{\pi D} \tag{1.7}$$

In terms of the barrel dimensions and parameters:

$$\theta(r) = \arctan\left(\frac{D_b}{D}\tan\theta_b\right) \tag{1.8}$$

The channel width at any radius thus follows:

$$W(r) = B\cos\theta(r) = \left(\frac{L}{p} - b(r)\right)\cos\theta(r) = \frac{L}{p}\cos\theta(r) - e \tag{1.9}$$

The average channel width is used for many of the calculations in this book. This average channel width is represented as simply $W$ here and is calculated using Equation 1.10. The use of the average channel width will be discussed in detail in Chapter 7.

$$W = \frac{W_b + W_c}{2} \tag{1.10}$$

Calculations in helical coordinates are very challenging. The procedure used in this text will be to "unwrap" the screw helix into Cartesian coordinates for the analysis. It is important to be able to calculate the helical length in the $z$ direction at any radius $r$ for the axial length $l$:

$$z(r) = \frac{l}{\sin\theta(r)} \tag{1.11}$$

## 1.4 Simple Flow Equations for the Metering Section

The efficient operation of a single-screw extruder requires that all three extruder sections, solids conveying, melting, and metering, must be designed to work efficiently and in coordination to have a trouble-free process. The specific analysis for each of these topics will be covered in later chapters. The simple flow calculations for the metering section should be performed at the start of any extruder troubleshooting process. It is presented at this time so that the reader may see how the equations developed in subsequent sections are used at the start of a typical troubleshooting problem.

For a properly operating smooth-bore single-screw extruder, the metering section of the screw must be the rate-limiting step of the process. Thus, calculation of the flows in the metering section of a process can be used to determine if the extruder is operating properly. A simple and fast method of estimating the flow components in a metering section was developed by Rowell and Finlayson [5] for screw pumps, and it was outlined in the Lagrangian frame by Tadmor and Klein [4]. These flows are based on a reference frame where the barrel is rotated in the opposite direction from the normal screw rotation, and they are historically called drag flow and pressure flow. Screw rotation analysis, as developed by Campbell and coworkers [6 – 15], is used here to arrive at the same flow equations while retaining the screw rotation physics of the extruder. For screw rotation, the flows are called rotational flow and pressure flow. This screw rotation analysis has been shown to provide a better understanding of the flow mechanism in the extruder, a better estimate of viscous dissipation and temperature increase in the extruder, and a better prediction of the melting characteristics. Several other methods are available for estimating the flow components in the metering section of a screw, but they can be more complicated and time consuming [16].

The method described here is the simplest of all methods. This simplicity is based on numerous assumptions (listed below), and thus it requires a minimum amount of data and computational effort. The calculation is only meant to give a quick and crude estimate of the flows, since in most cases assumptions 4 through 7 are violated. An improved yet more difficult method is introduced in Chapter 7. The assumptions for the simple calculation method are as follows:

1. Flow is fully developed.
2. Flow channels are completely filled.
3. No slip at the boundary surfaces.
4. No leakage flow over the flight tips.
5. All channel corners are square.

6. Flows are isothermal and Newtonian.
7. Channel dimensions are not changing in the metering section.

The fully developed flow components in a constant-depth metering section can be estimated using flow analysis for a long rectangular channel, as outlined in Chapter 7. For those calculations, a geometry transformation is first performed. That is, the channels of the screw are “unwound from the helix” and “straightened into a long trough.” The barrel now becomes an infinitely large flat plate. Next, the screw or trough is moved at a fixed angle to the stationary barrel. These equations were developed using a Cartesian coordinate system; that is, the $z$ direction is in the down-channel direction and parallel to the flight edge, the $y$ direction is normal to the barrel surface, and $x$ is the cross-channel direction and thus perpendicular to the flight edge.

The geometric parameters for a screw in the “wound” form are shown by Figure 1.5 for a single-flighted screw.

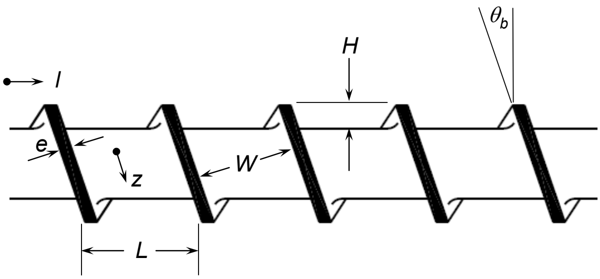


**Figure 1.5** Geometric parameters for a single-flighted screw in the wound state

Two driving forces for flow exist in the metering section of the screw. The first flow is due just to the rotation of the screw and is referred to as the rotational flow component. The second component of flow is due to the pressure gradient that exist in the $z$ direction, and it is referred to as pressure flow. The sum of the two flows must be equal to the overall flow rate. The overall flow rate, $Q$, the rotational flow, $Q_d$, and the pressure flow, $Q_p$, for a constant depth metering channel are related as shown in Equation 1.12. The subscript $d$ is maintained in the nomenclature for historical consistency even though the term is for screw rotational flow rather than the historical drag flow concept.

$$Q = Q_d - Q_p \tag{1.12}$$

The volumetric rotational flow term ($Q_d$) depends on the several geometric parameters and rotation speed. Since most extruder rates are measured in mass per unit time, the term $Q_{md}$ is defined as the mass rotational flow:

$$Q_d = \frac{pV_{bz}WHF_d}{2} \tag{1.13}$$

$$Q_{md} = \frac{p\rho_m V_{bz} WHF_d}{2} \tag{1.14}$$

where $\rho_m$ is the melt density at the average fluid temperature of the resin, $V_{bz}$ is the $z$ component of the screw velocity at the barrel wall, $H$ is the depth of the channel, and $F_d$ is the shape factor for plane Couette flow. The analysis using plane Couette flow does not take into account the effect of the flights (channel helix) on the flow rate. The $F_d$ term compensates for the reduction in flow rate due to the drag-induced resistance of the flights. For an infinitely wide channel with no flights, $F_d$ would be equal to 1. As the channel width approaches the depth, $F_d$ is about 0.5.

The analysis developed here is based on screw rotation physics [13], and thus several other definitions are developed here. The velocities at the screw core, indicated by the subscript $c$, in the $x$ and $z$ directions are as follows:

$$V_{cx} = \pi N D_c \sin\theta_c \tag{1.15}$$

$$V_{cz} = -\pi N D_c \cos\theta_c \tag{1.16}$$

where $N$ is the screw rotation rate in revolutions per second. Cross-channel velocity for the screw in the laboratory frame (screw rotation frame) is

$$V_x = V_{cx}\left(1+\frac{H}{R_c}\right)\frac{y}{H}\left(2-3\frac{y}{H}\right)+V_{cx}\left(1+\frac{y}{R_c}\right) \tag{1.17}$$

where $R_c$ is the screw core radius.

The down-channel velocity in the laboratory frame for very wide channels ($H/W$ < 0.1) as a function of the height of the channel $y$ is as follows:

$$V_{dz} = \frac{y}{H}\left|V_{cz}\right|\left(1+\frac{H}{R_c}\right)-\left|V_{cz}\right|\left(1+\frac{y}{R_c}\right) \tag{1.18}$$

Pressure flow velocity in the $z$ direction for a very wide channel ($H/W$ < 0.1) as a function of $y$ is

$$V_{pz} = \frac{H^2}{8\eta}\frac{\partial P}{\partial z}\left[\left(\frac{y}{H}\right)^2-\frac{y}{H}\right] \tag{1.19}$$

The $z$ component of the screw velocity at distance $H$ from the screw root is computed as

$$V_{bz} = \pi N D_b \cos\theta_b \tag{1.20}$$

or

$$V_{bz} = V_{cz}\left(1+\frac{H}{R_c}\right) \tag{1.21}$$

The volumetric pressure flow term, $Q_p$, and the mass flow pressure flow term, $Q_{mp}$, are computed as follows:

$$Q_p = \frac{pWH^3F_p}{12\eta}\left[\frac{\partial P}{\partial z}\right] \tag{1.22}$$

$$Q_{mp} = \frac{p\rho_m WH^3F_p}{12\eta}\left[\frac{\partial P}{\partial z}\right] \tag{1.23}$$

where $F_p$ is the shape factor for pressure flow, $\partial P / \partial z$ is the pressure gradient in the channel in the $z$ direction, and $\eta$ is the shear viscosity of the molten polymer at the average channel temperature and at an average shear rate, $\dot{\gamma}$:

$$\dot{\gamma} = \frac{\pi D_c N}{H} \tag{1.24}$$

The shear rate in the channel contains contributions from the rotational motion of the screw and the pressure-driven flow. The calculation of the shear rate, $\dot{\gamma}$, using Equation 1.24, is based on the rotational component only and ignores the smaller contribution due to pressure flow. For the calculations here, Equation 1.24 can be used.

The relationship between the pressure gradient in the $z$ direction to the axial direction, $l$, is as follows:

$$\frac{\partial P}{\partial z} = \frac{\partial P}{\partial l}\sin\theta_b \tag{1.25}$$

The pressure gradient is generally unknown, but the maximum that it can be for a single-stage extruder screw is simply the discharge pressure, $P_{dis}$, divided by the helical length of the metering section. This maximum gradient assumes that the pressure at the start of the metering section is zero. For a properly designed process, the actual gradient will be less than this maximum, and the pressure at the start of the metering section will not be zero.

$$\frac{\partial P}{\partial z} = \frac{P_{dis}\sin\theta_b}{l_m} \tag{1.26}$$

where $l_m$ is the axial length of the metering section. The shape factors $F_d$ and $F_p$ [4, 17] are computed to adjust for the end effect of the flights. The factors are from the summation of an infinite series as part of an exact solution for the constant temperature and constant viscosity solution in the $z$ direction in the unwound screw channel. The factors are calculated as follows:

$$F_d = \frac{16W}{\pi^3 H} \sum_{i=1,3,5,\ldots}^{\infty} \frac{1}{i^3} \tanh\left(\frac{i\pi H}{2W}\right) \tag{1.27}$$

$$F_p = 1 - \frac{192H}{\pi^5 W} \sum_{i=1,3,5,\ldots}^{\infty} \frac{1}{i^5} \tanh\left(\frac{i\pi W}{2H}\right) \tag{1.28}$$

The shape factors range from 0 to 1 and approach 1 for shallow channels; that is, $H / W \approx 0$. It is important to include the shape factors when evaluating commercial screw channels. This becomes extremely important for deep channels where $H/W$ does not approach 0. The total mass flow rate, $Q_m$, is calculated by combining the flow components as provided in Equation 1.29 for the total mass flow rate. As stated previously, the rate, rotational flow, and pressure flow calculations should be performed at the start of every troubleshooting project.

$$Q_m = \frac{p\rho V_{bz} WHF_d}{2} - \frac{p\rho WH^3 F_p}{12\eta}\left[\frac{\partial P}{\partial z}\right] \tag{1.29}$$

## 1.5 Example Calculations

Three examples are presented that introduce the use of the equations developed in this chapter. These calculations should be used at the start of the performance analysis of all troubleshooting problems. This analysis will be expanded in subsequent chapters through Chapter 7 using additional tools and understandings to complete the troubleshooting process.

### 1.5.1 Example 1: Calculation of Rotational and Pressure Flow Components

A manager decided to buy a new 88.9 mm (3.5 inch) diameter general purpose extruder to extrude products using several different low-density polyethylene (LDPE) resins. The die manufacturer has indicated that the die entry pressure will be 12.4 MPa. Both vendors used nominal viscosity data for a commercial LDPE resin at a temperature of 210 °C when doing their predictions because the manager had not yet settled on the resins or manufacturer for the new materials. The manager has specified that the extruder must be capable of running flood-fed at a maximum rate of 250 kg/h. Flood feeding refers to the operation of the extruder with resin covering the screw in the feed hopper. In this operation, increasing the screw speed will increase the rate of the process. The shear viscosity specified was

2000 Pa·s. The melt density for LDPE resin at 210 °C is 0.75 g/cm$^3$. The screw was specified with a 6 diameter long feed section with a constant channel depth of 16.51 mm, a 9 diameter long transition section, and a 9 diameter long metering section with a constant channel depth of 5.08 mm. The screw lead length is 1.2 times the screw diameter at 107 mm and the screw flight width perpendicular to the flight edge is 9.0 mm. The extruder manufacturer has stated that the extruder is capable of a maximum screw speed of 108 rpm. Will this extruder meet the desired rate expectations of the manager for the LDPE resin?

In order to address this key question, the information provided in this chapter will be used to calculate the geometrical and flow data for this analysis. When making the calculations for any engineering analysis it is absolutely imperative that the same units system be used for all the calculations. It is generally accepted today that the calculations are performed using the SI units system [18]: mass in kilograms, length in meters or some fraction thereof, time in seconds, energy in joules, pressure in Pascal, and viscosity in Pascal seconds.

To start the calculation, the geometrical parameters are calculated based on the known specifications for the metering channel of the screw. Only the metering channel is considered here since the metering channel is the rate-controlling operation for a properly designed screw and a smooth-bore extrusion process. The specifications and calculated values for the metering channel of the screw are provided in Table 1.1 along with the equations used for the calculations.

**Table 1.1** Geometric Parameter Values for the Screw in Example 1

| Parameter | Value | Equation |
|---|---|---|
| Barrel diameter, $D_b$ | 88.9 mm | |
| Core diameter, $D_c$ | 78.74 mm | |
| Lead length, $L$ | 107 mm | |
| Meter channel depth, $H$ | 5.08 mm | |
| Flight width, $e$ | 9.0 mm | |
| Flight starts, $p$ | 1 | |
| Helix angle at the barrel, $\theta_b$ | 21.0° | 1.1 |
| Helix angle at the screw core, $\theta_c$ | 23.4° | 1.4 |
| Channel width at the barrel, $W_b$ | 90.9 mm | 1.2 |
| Channel width at the screw core, $W_c$ | 89.2 mm | 1.5 |
| Average channel width, $W$ | 90.0 mm | 1.10 |
| Channel aspect ratio, $H/W$ | 0.056 | |
| Unwrapped channel length for one turn, $z_b$ | 299 mm | 1.11 |
| Total helical length of the metering section, $Z_b$ | 2.23 m | 1.11 |
| Shape factor for rotational flow, $F_d$ | 0.966 | 1.27 |
| Shape factor for pressure flow, $F_p$ | 0.965 | 1.28 |

Since the manager is asking for an extruder and screw that will provide 250 kg/h, the expected maximum rate will be calculated at the maximum screw speed of 108 rpm. At a screw speed of 108 rpm ($N$ = 1.80 rev/s), the $z$ component of the flight tip velocity ($V_{bz}$) at $H$ is calculated at 469 mm/s using Equation 1.20. Now all terms required to calculate the rotational mass flow rate are known and are calculated using Equation 1.14:

$$Q_{md} = \frac{(750\ \text{kg/m}^3)(0.469\ \text{m/s})(0.090\ \text{m})(5.08\times 10^{-3}\ \text{m})(0.966)}{2}$$
$$= 0.077\ \text{kg/s} => 280\ \text{kg/h}$$

For this calculation, the density of the molten LDPE resin is known to be 750 kg/m$^3$ at 210 °C. Next, the pressure flow term needs to be calculated based on the maximum pressure gradient possible in the metering channel. The maximum pressure gradient will occur when the pressure at the entry to the metering section is near zero. In practice, the pressure at the entry to the meter will be considerably higher. With zero pressure at the entry and 12.4 MPa at the discharge (die entry pressure), the maximum pressure gradient is estimated by dividing the pressure change by the helical length ($Z_b$) of the metering channel. This maximum pressure gradient $\partial P / \partial z$ is calculated at 5.56 MPa/m. Since the pressure is increasing in the helical direction, the pressure gradient is positive. Next, the mass flow rate due to the pressure gradient is calculated using Equation 1.23 and a shear viscosity of 2000 Pa·s as follows:

$$Q_{mp} = \frac{(750\ \text{kg/m}^3)(0.090\ \text{m})(5.08\times 10^{-3}\ \text{m})^3(0.965)}{12(2000\ \text{Pa}\cdot\text{s})}\left(\frac{5.56\times 10^6\ \text{Pa}}{\text{m}}\right)$$
$$= 0.0020\ \text{kg/s} => 7\ \text{kg/h}$$

The overall mass rate expected from the extruder and screw specification was calculated using Equation 1.12 at 273 kg/h. The manager specified a rate of 250 kg/h for the process. Since the extruder is capable of 273 kg/h at the maximum screw speed, the extruder is specified properly from a rate viewpoint. Further calculations indicated that 250 kg/h of LDPE could be extruded at a screw speed of 99 rpm for a maximum pressure gradient of 5.56 MPa/m, discharging at 210 °C and a pressure of 12.4 MPa. The pressure mass flow $Q_{mp}$ is very low, at about 2% of the rotational mass flow $Q_{md}$. If the screw geometry is kept constant, this ratio will increase if the discharge pressure increases or the viscosity decreases. As this book progresses, the solution for Example 1 will be expanded as new materials are introduced in subsequent chapters through Chapter 7.

### 1.5.2 Example 2: Flow Calculations for a Properly Operating Extruder

For this example, a plant is using a smooth-bore extruder to process an LDPE resin. At a screw speed of 100 rpm, the extruder is operating flood-fed with a rate of 800 kg/h. For these conditions, the plant personnel have measured the discharge pressure at 15.9 MPa and the discharge temperature at 210 °C. The plant manager wants to know if this extruder is operating properly and whether the metering section of the screw is controlling the rate. For this case, the extruder is 152.4 mm in diameter, $D_b$, the lead length, $L$, is 152.4 mm, the width of the flight, $e$, is 15.2 mm, and the channel depth, $H$, in the metering section is 6.86 mm. The metering section length is 76.2 cm or 5 turns. The melt density for LDPE resin at 210 °C is 0.750 g/cm$^3$.

The shear rate for this example is estimated using Equation 1.24 to be 106 1/s. The viscosity for this LDPE resin at 210 °C and a shear rate of 106 1/s is about 300 Pa·s. From the screw geometry, screw speed, and melt density, the rotational flow rate, $Q_{md}$, is computed at 888 kg/h. Since the rotational flow and pressure flow must equate to the total flow using Equation 1.29, the pressure flow rate, $Q_{mp}$, is 88 kg/h. The positive sign for the pressure flow rate term means that the pressure gradient is reducing the flow. Likewise, a negative pressure flow rate term would mean that the pressure gradient is causing the flow rate to be higher than the rotational flow rate. For this resin and a viscosity of 300 Pa·s, the pressure gradient in the channel is calculated using Equation 1.29 as 1.40 MPa/turn. Thus, the discharge end of the metering channel is at a higher pressure than the entry.

To answer the question as to whether the extruder is operating properly, several additional calculations are performed. For this screw, there are 5 screw turns in the metering section, which is calculated by dividing the axial length (76.2 cm) by the lead length ($L$ = 152.4 mm). Multiplying the number of turns by the pressure gradient in the metering section reveals that the total pressure increase in the metering section is 7.0 MPa. To achieve the measured discharge pressure of 15.9 MPa, the pressure at the entry of the metering section must be 8.9 MPa. Because a positive pressure over the entire length of the metering section is occurring, the calculations indicate that the screw is full with resin and functioning properly. That is, the metering section is controlling the rate. The axial pressure profile for this case is shown in Figure 1.6.

### 1.5.3 Example 3: Flow Calculations for an Improperly Operating Extruder

An extruder with a metering section having the same geometry as the extruder in Example 2 is operating flood-fed at a rate of 550 kg/h. The screw speed is 100 rpm, the discharge temperature is 210 °C, and the discharge pressure is 10.3 MPa. Is this extruder operating properly so that its metering section is controlling the rate? Because the metering section geometry, screw speed, and discharge temperature have not changed, the method still calculates the rotational flow rate component as 888 kg/h. However, the pressure flow component is now calculated as 338 kg/h, and the pressure gradient corresponding to this flow is 5.4 MPa/turn. To determine if the extruder is operating properly, the pressure generating capacity needs to be calculated by multiplying the 5 screw turns in the metering section length by the pressure gradient. The result is a total pressure increase of 27 MPa in the metering section. This pressure increase is greater than the 10.3 MPa pressure measured at the discharge of the extruder. In fact, only 1.9 diameters of the metering section length are required to generate a discharge pressure of 10.3 MPa (calculated by dividing 10.3 MPa by 5.4 MPa/turn). This means that the remaining 3.1 diameters of the metering section are at zero pressure and are only partially filled. A partially filled system will always be at zero pressure. Because a positive pressure over the entire length of the metering section is not possible, the calculations indicate that the metering section is not full and is not functioning properly. A process upstream of the metering section is controlling the rate.

Figure 1.6 shows the axial pressures for the extruders described in Examples 2 and 3. In this figure, the solid lines were calculated while the dotted lines were estimated based on experience. For Example 2, where the extruder operates properly, the extruder pressure is positive at all axial positions. Thus, all the channel sections are operating full and under pressure as designed. For Example 3, where the extruder operates improperly, the extruder pressure is zero for portions of the melting and metering sections. In these portions of the extruder, the screw channel is not pressurized, and the extruder is operating partially filled. This means that the metering section is not controlling the rate as designed, and the screw is not operating properly. Extruders that are operated partially filled in the metering section can have low production rates, high scrap rates, and material degradation, and cause high labor costs.

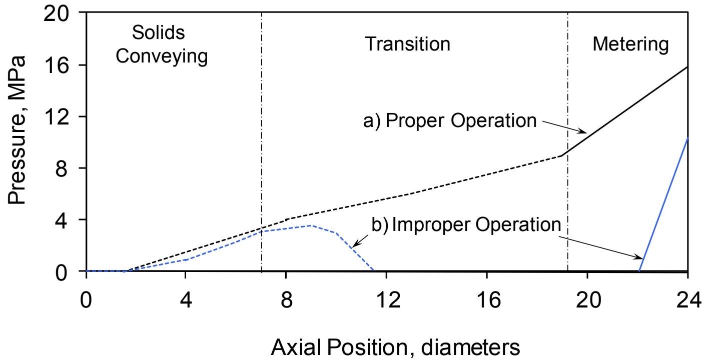


**Figure 1.6** Axial pressure profiles for a) Example 2 where the extruder is operating properly (all channels are full and pressurized), and b) Example 3 where the extruder is operating improperly. For Example 3, the channel is not pressurized between diameters 12 and 22, indicating that the channels are partially filled at these locations

### 1.5.4 Metering Channel Calculation Summary

Calculation of the rotational flow rate and an estimate of the pressure profile in the metering channel should be performed for all design and troubleshooting projects. As shown in the example problems, the rate can be quickly and easily estimated for a new installation. The calculation method should always be performed for machines that are operating at low rates and have degradation products in the extrudate. As described in Section 1.5.3, the calculation is capable of predicting partially filled channels in the metering section. Partially filled metering channels will cause the resin to degrade, and the degradation products will eventually be discharged from the machine, contaminating the final product.

## Nomenclature

$b_b$ axial flight width at the barrel wall

$b_c$ axial flight width at the screw root

$B$ axial channel width as a function of the radial position

$B_b$ axial channel width at the barrel wall

$B_c$ axial channel width at the screw core

$D$ local diameter

$D_b$ inner diameter of the barrel

$D_c$ diameter of the screw core

$e$ flight width of the screw and perpendicular to the flight edge

$F_d$ shape factor for rotational flow

$F_p$ shape factor for pressure flow

$H$ local distance from the screw root to the barrel

$l$ axial distance

$l_m$ axial distance for the metering section

$L$ lead length

$N$ screw rotation speed in revolutions/s

$p$ number of flight starts

$P_{dis}$ discharge pressure

$P$ pressure in the channel

$Q$ volumetric flow rate

$Q_d$ volumetric rotational flow rate

$Q_m$ mass flow rate

$Q_{md}$ mass rotational flow rate

$Q_{mp}$ pressure-induced mass flow rate

$Q_p$ volumetric pressure flow rate

$R_c$ radius of the screw core

$V_{dz}$ down-channel velocity ($z$ direction) as a function of $y$

$V_{pz}$ $z$ component of the velocity due to a pressure gradient

$V_x$ cross-channel velocity ($x$ direction) in the channel as a function of $y$

$V_{cx}$ $x$ component of velocity of the screw core

$V_{cz}$ $z$ component of velocity of the screw core

$V_{bz}$ $z$ component of velocity of the screw flight at the barrel wall

$W$ average channel width

$W_b$ channel width perpendicular to flight at the barrel wall

$W_c$ channel width perpendicular to flight at the screw core

$W(r)$ channel width perpendicular to flight at radius $r$

$x$ independent variable for the cross-channel direction perpendicular to the flight edge

$y$ independent variable for the direction normal to the barrel surface (channel depth direction)

$z$ independent variable in the down-channel direction (or helical direction)

$z_b$ helical length of the channel at the barrel wall

$z(r)$ helical length of the channel at radial position $r$

$Z_b$ helical length of the metering channel at the barrel wall

$\dot{\gamma}$ average shear rate in the channel

$\eta$ shear viscosity of the polymer at the average channel temperature and average shear rate, $\dot{\gamma}$

$\theta_b$ helix angle at the barrel

$\theta_c$ helix angle at the screw core

$\theta(r)$ helix angle at radial position $r$

$\lambda$ mechanical clearance between the top of the screw flight and the barrel wall

$\rho_m$ melt density of the fluid

# References


1. Kamal, M. R., Isayev, A. I., and Liu, S-J., "Injection Molding Technology and Fundamentals," Hanser Publications, Munich (2009)
2. Kirkland, C., "Damage Control Saturn Style," *Injection Molding Magazine*, September (1994)
3. Chung, C. I. and Barr, R. A., "Energy Efficient Extruder Screw," U. S. Patent 4, 405, 239 (1983)
4. Tadmor, Z. and Klein, I., "Engineering Principles of Plasticating Extrusion," Van Nostrand Reinhold Co., New York (1970)
5. Rowell, H.S. and Finlayson, D., "Screw Viscosity Pumps," *Engineering*, **114**, 606 (1922)
6. Campbell, G. A., Tang, Z., Wang, C., and Bullwinkel, M., "Some New Observations Regarding Melting in Single Screw Extruders," *SPE ANTEC Tech. Papers*, **49**, 213 (2003)
7. Campbell, G. A. and Tang, Z., "Solid Bed Melting in Single Screw Extruders – An Alternative First Order Mechanism," *SPE ANTEC Tech. Papers*, **50**, 162 (2004)
8. Campbell, G. A. Wang, C., Cheng, H., Bullwinkel, M., and te-Riele, M. A., "Investigation of Flow Rate and Viscous Dissipation in a Single Screw Pump-Extruder," *Int. Polym. Process.*, **16**, 323 (2001)
9. Campbell, G. A. and Dontula, N., "Solids Transport in Extruders," *Int. Polym. Process.*, **10**, 30 (1995)
10. Campbell, G. A., Spalding, M. A., and Carlson, F., "Prediction of Screw Temperature Rise in Single Screw-Pump Extruders," *SPE ANTEC Tech. Papers*, **54**, 267 (2008)
11. Campbell, G. A., Sweeney, P. A., and Felton, J. N., "Experimental Investigation of the Drag Flow Assumption in Extruder Analysis," *Polym. Eng. Sci.*, **32**, 1765 (1992)
12. Campbell, G. A., Sweeney, P. A., and Felton, J. N., "Analysis of an Alternative Extruder Screw Pump Design," *Int. Polym. Process.*, **7**, 320 (1992)
13. Campbell, G. A., Sweeney, P. A., Dontula, N., and Wang, Ch., "Frame Indifference: Fluid Flow in Single Screw Pumps and Extruders," *Int. Polym. Process.*, **11**, 199 (1996)
14. Campbell, G. A., Cheng, H., Wang, C., Bullwinkel, M., and te-Riele, M. A., "Temperature Rise in a Single Screw Pump-Extruder," *SPE ANTEC Tech. Papers*, **47**,152 (2001)
15. Campbell, G. A., Spalding, M. A., and Tang, Z., "An Alternative Analysis of Single-Screw Melting," *SPE ANTEC Tech. Papers*, **55**, 147 (2009)
16. Spalding, M. A., Dooley, J., Hyun, K.S, and Strand, S. R., "Three Dimensional Numerical Analysis of a Single-Screw Extruder, " *SPE ANTEC Tech. Papers*, **39**, 1533 (1993)
17. Squires, P. H., "Screw Extruder Pumping Efficiency," *SPE J.*, **14**, 24 (1958)
18. Conant, F. S., "Using the SI Units," *Polym. Eng. Sci.*, **17**, 222 (1977)

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