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Effect of Geometry and Rotational Speed on the Axial Pressure Profile of a Single Screw Extrusion

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Abstract

The evaluation of screw design is investigated using modeling and simulation techniques. Simulation studies were used to predict the performance of the screw under certain working conditions and flow results were developed. The pressure reached inside the barrel is directly linked to the screw geometry, set of processing conditions. The derivation of simple governing algebraic equations covering channel geometry, polymer flow rate and developed pressure were outlined to predict the response of the extruder screw. Screw rotational speed and screw design were analyzed to predict the axial pressure profile along the extruder length.

Keywords: Extruder Design, Polymer Extrusion, Screw Axial Pressure.

1. Introduction

Polymer extrusion is considered one of the major methods of processing polymer materials by using a screw inside a barrel. The extruder is the most important part of machinery in the polymer processing industry as it controls the solid conveying, melting delay, melting behavior and conveying. Screw extruders are divided into two types; single screw and multi screw extruders. Single screw extruder is the widely used type due to its low cost, reliability and satisfactory performance. The screw is divided into three zones; feeding, compression and metering zone. The first zone (closest to the feed hopper) has deep flights where the material will be mostly in the solid state. This screw section is referred as the feed section of the screw. The last zone (closest to the die) has shallow flights where the material will be in the molten state. This screw section is referred as the metering section or pump section. The middle screw section connects the feed section and the metering section. This section is called the transition section or compression section. The main parameters of single screw extruder are its length, length to diameter ratio, lengths of feed, compression and metering zones, flight width, flight pitch, and channel depths in each section. Typically, screw lengths for thermoplastics range from 15D to 30D, Compression depths for general purpose screws normally lie in the range of 2–4 [1]. The change in depth along screw length is selected by the type of material being extruded. Gradual tapers in compression zones are often used for polyolefin. These act to gradually reduce the solid bed and maintain downstream velocity. Longer feed zones are used followed by a rapid transition, or step, often occurring in <10D [1]. High stresses and temperatures in the extrusion are dependent on a number of factors, screw design being one of the most significant parameters, which could decide the effectiveness of the extrusion process and the quality of the finished product.

Some screw parameters are summarized in Fig.1. as will be seen later, The use of different dies means that the extruder screw barrel can be used as the basic unit of several processing techniques.

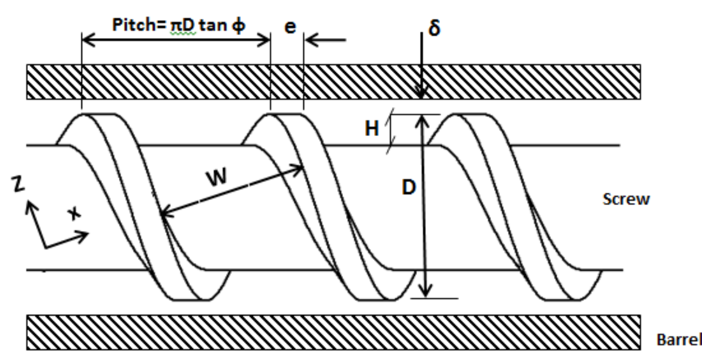
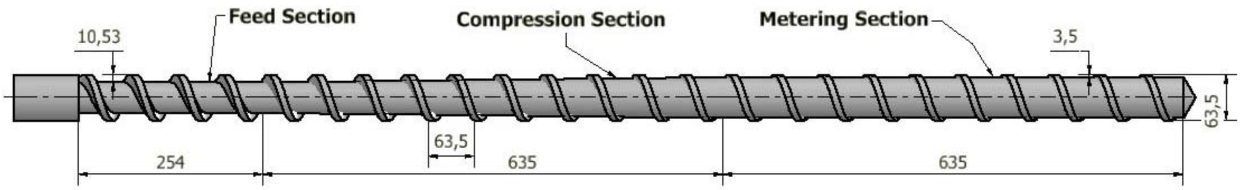


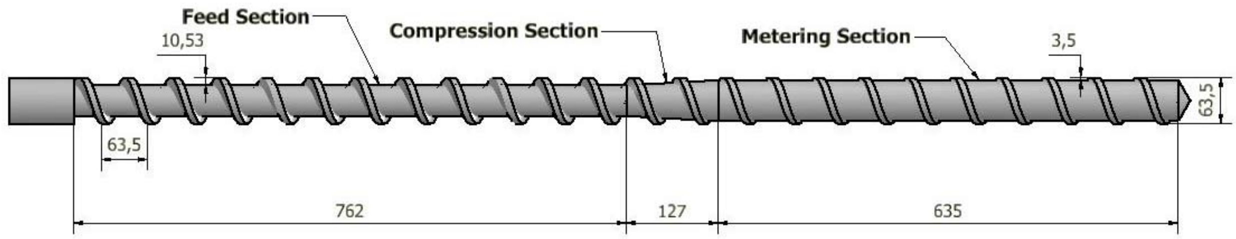
Fig.1 Details of Extruder screw

2. Extruder Configuration

Two sets of single-screw extruders were used throughout this analysis to evaluate the axial pressure profile when equipped with different dies. The geometrical configurations of the screws are shown in Fig.2 and summarized in Table 1. Three rod dies were used, of diameters 12, 4 and 3 mm with 20 mm die length. In the flow analysis, a low-density polyethylene (LDPE) was used. The physical and rheological properties are shown in Table 2.



(a)



(b)

Fig.2 Schematic representation of 24:1 L/D screws
(a) gradual compression, (b) rapid compression

Table.1 Geometrical configurations

Parameter	Traditional Screw	Rapid compression
Screw diameter	63.5 mm	63.5 mm
Solid conveying length	4D	12D
Compression length	10D	2D
Melt conveying length	10D	10D
Pitch	63.5 mm	63.5 mm
Helix angle (ϕ)	17.7°	17.7°
Feed depth (H_{feed})	10.53 mm	10.53 mm
Metering depth (H)	3.5 mm	3.5 mm
Compression Ratio	3:1	3:1
Flight width (e)	10 mm	10 mm
Flight clearance (δ)	0.06 mm	0.06 mm

a) Physical Properties	LDPE
Density of solid polymer, ρ_s (Kg/m^3)	920
Bulk Density, ρ_B (Kg/m3)	600
Density of molten polymer, ρ_m (Kg/m^3)	760
Thermal Conductivity of molten polymer, K_m (W/m.C°)	0.2
Specific Heat of Polymer, C_s (J/Kg.C°)	2300
Melting Temperature, T_m (C°)	110
Heat of fusion, $\lambda \times \mathbf{10^5}$ (J/Kg)	2
b) Rheological parameters	
Power-Law exponent, n	0.35
Temperature Coefficient, b (1/ C°)	0.03
Consistency, $m_o \times \mathbf{10^3}$ ($Pa.s^n$)	10

Table.2 Properties of Low-Density Polyethylene

3. Analysis of flow in Extruder

3.1 Flow in metering section

The flow of polymer inside the barrel is equivalent to the flow of a viscous liquid between two parallel plates when one plate is stationary and the other is moving. Many studies for the flow in the metering section by Rowell and Finlayson [2] for screw pumps, and it was outlined by Tadmor and Klein [3] .The metering section of the screw must be the rate-limiting step of the process, so the estimated flow will be based on metering zone; Simple equations were concluded including drag, pressure and leakage flow by R.J. Crawford [4].

$$Q = \frac{1}{2}\pi^2 D^2 NH \sin\emptyset \cos\emptyset - \frac{\pi D H^3 \sin^2\emptyset}{12\eta} \cdot \frac{p}{L} \quad (1)$$

$$Q_{max} = \frac{1}{2}\pi^2 D^2 NH \sin\varphi \cos\emptyset \quad (2)$$

$$Q_p = -\frac{\pi D H^3 \sin^2\emptyset}{12\eta} \cdot \frac{dp}{dL} \quad (3)$$

$$P_{max} = \frac{6\pi DLN\eta}{H^2 \tan\emptyset} \quad (4)$$

$$P_{op} = \left\{ \frac{2\pi\eta D^2 NH \sin\emptyset \cos\emptyset}{(R^4/2L_d) + (DH^3 \sin^2\emptyset)/3L} \right\} \quad (5)$$

Where Q is the total flow rate, Q_{max} is the maximum flow rate, D the diameter of extruder screw, N screw rotational motion, H screw depth at metering section, $\emptyset$ the helix angle, Q_p is pressure flow, η is the viscosity, L is the length of the extruder screw, R is the die radius and L_d is die length.

In Fig. 3, calculations of extruder characteristics at different speeds and die characteristics using three different dies to estimate if the extruder works properly with the given conditions.

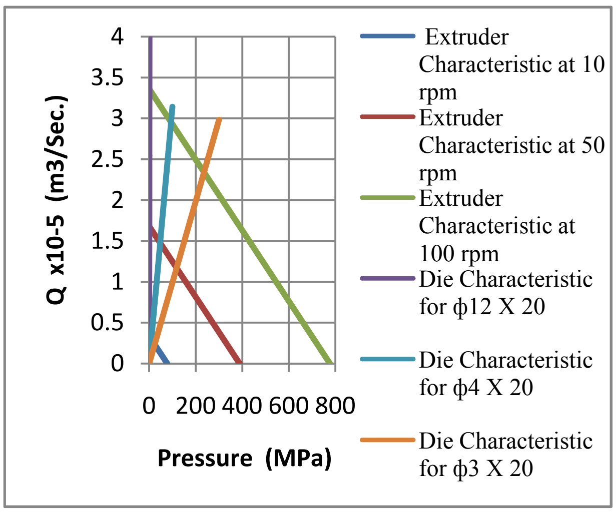


Fig.3 Screw and Die characteristics

3.2 Combined solid and melt conveying

The extrusion process comprises solids conveying of the feed material to the machine, melting of the polymer, and metering of the resulting melt. Mathematical representation for solid conveying made by W. H. Darnell, and E. A. Mol [5] to predict the axial pressure profile along the extruder screw.

$$\ln\left(P/P_o \right) = \frac{K.z}{A} \begin{bmatrix} W.f_b \cos(\theta+\phi) \\ -W.f_s \end{bmatrix} \quad (6)$$

where P_o is the starting pressure in the element, k is the ratio of radial to axial stresses in the solid bed, z is the down channel length of the element, A is the cross-sectional area of the bed, W is the channel width, f_b and f_s are the dynamic coefficients of friction between the solid polymer particles and the barrel and screw surfaces, q is the solids conveying angle and $\emptyset$ is the helix angle of the screw flight at the top of the flight.

The first mathematical model based on melting mechanism and reorganizing solid bed made by Z. Tadmor [6], another model that gave analytical solutions was developed by C. I. Chung [7] to express the solid bed width, pressure developed along the screw and actual flow rate. This could lead to the conclusion of a value of the pressure at any point in the melting zone and the value given by Eq. (12).

$$\Omega = \rho_m . U_{sb} \left(\frac{\delta_o}{X_o} \right) \left\{ \begin{matrix} \dfrac{A}{G(a)} \\ +\sigma . H(a) . A^3 \end{matrix} \right\} \quad (7)$$

where Ω is the local melting flux, ρ_m is melt density, U_{sb} is the sliding velocity of the solid bed relative to the barrel, δ_o is a characteristic melt film thickness, X_o is the solid bed width in the solids conveying angle direction, σ is called the reduced pressure, and A, G(a) and H(a) represent compound expressions.

$$Q_c = \frac{1}{2} v_{bz} WH.F_d - \frac{WH^3}{12\eta} \frac{\Delta P}{\Delta z} F_p \quad (8)$$

$$F_d = 1 - \frac{0.571}{W/H} \quad (9)$$

$$F_p = 1 - \frac{0.625}{W/H} \quad (10)$$

$$v_{bz} = \frac{N\pi D_s}{60} \cos\phi \quad (11)$$

Q_c is the characteristic expression for the channel flow rate, V_{bz} the velocity in Z-direction, Coefficients F_d and F_p are shape factors.

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$$\Delta P = - \left[\frac{Q_C - \frac{1}{2} V_{bz} (W - X_1) \frac{H_1 H_2}{\frac{1}{2}(H_1 + H_2)}}{\frac{(W - X_1)(H_1 H_2)^2}{6\eta (H_1 + H_2)}} \right] \Delta z \qquad (12)$$

Model predictions should be compared to previously, published results. In Fig. 4 calculations of pressure development along the screw are compared to experimental data taken from C. D. Han [8], for LDPE at 25 rpm using 63.5 mm diameter screw.

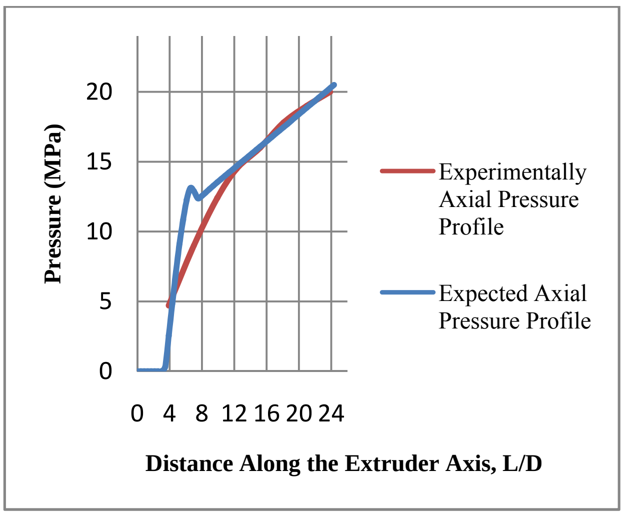

Fig.4 Model predictions plotted against experimental data

4. Results

The pressure profiles for LDPE measured along the extruder axis are plotted in Fig. 5 for traditional screw equipped with 12 mm die at different rotational speeds with maximum pressure developed at 10 rpm and peak pressure approximately at 13 turns of the screw shifted to 12 turns for 100 rpm. Fig. 6 and Fig. 7 show the pressure when the extruder equipped with 4mm and 3 mm dies. The values of maximum pressure and head pressure are listed in Table 3. Fig.8 shows the difference between the three profiles at the same speed, the pressure peaks for the three cases occurred at the same screw position as the equipped dies have no influence on the peak of the pressure as it mainly depends on the end of melting of the processed polymer.

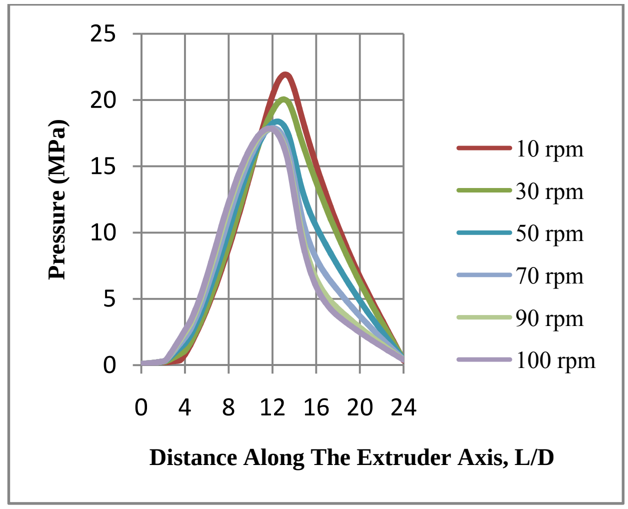

Fig. 5 Pressure profiles at different screw speeds for Traditional screw using 12 mm die.

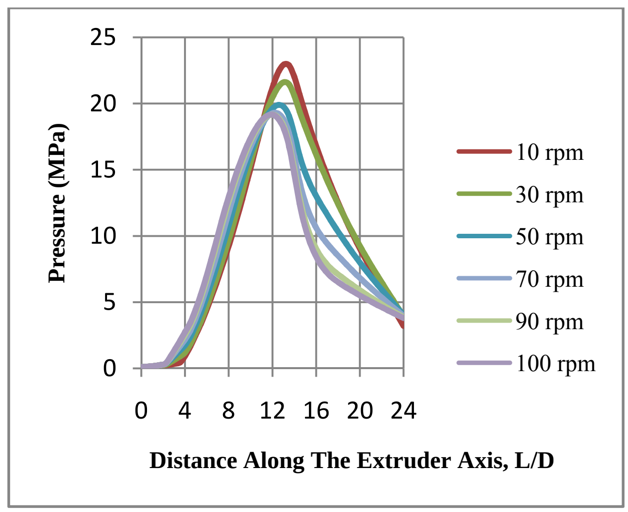

Fig. 6 Pressure profiles at different screw speeds for Traditional screw using 4 mm die.

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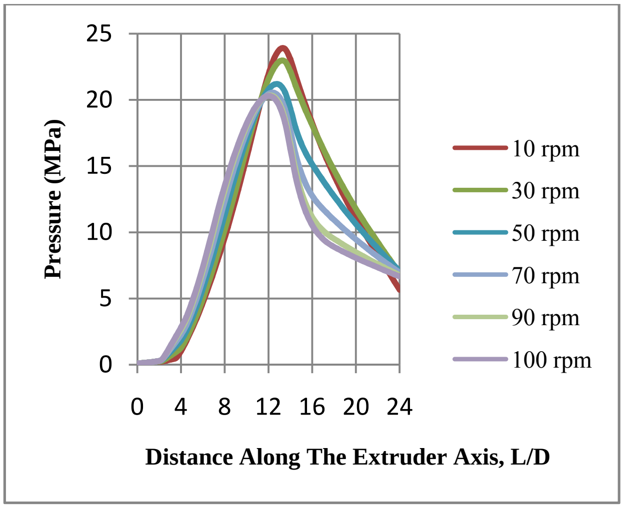

Fig. 7 Pressure profiles at different screw speeds for Traditional screw using 3 mm die.

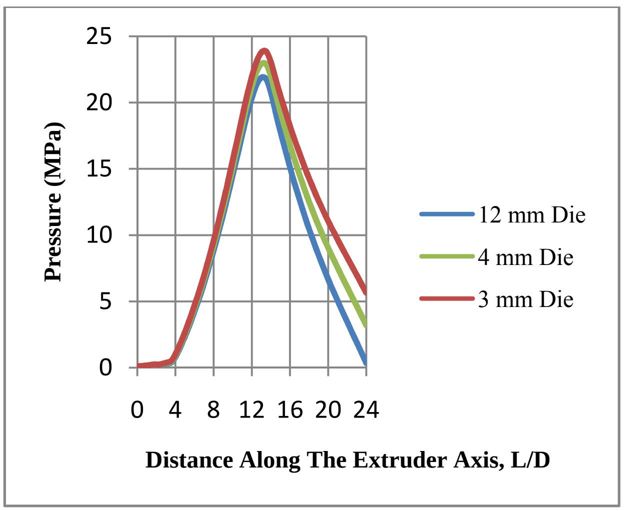

Fig. 8 Comparison between Different die diameters at 10 rpm for Traditional Screw

Die (mm)	Maximum Pressure* (MPa)	Head Pressure (MPa)
12	21.91	0.35
4	22.95	3.21
3	23.82	5.66
*Maximum Pressure occurred at 13 Turns of screw		

Table.3 Values of Pressure for Traditional screw at 10 rpm.

The pressure buildup in the rapid compression screw at different speeds is shown in Fig.9, the maximum pressure developed when the extruder operates at its maximum speed and pressure peaks occurred at the end of compression section. Fig. 10 and Fig. 11 show the behavior of meltedpolymer with other dies, causing different pressure head and the same pressure peak value and position. The values of maximum pressure and head pressure for rapidcompression screw are listed in Table 4 for all the used dies.

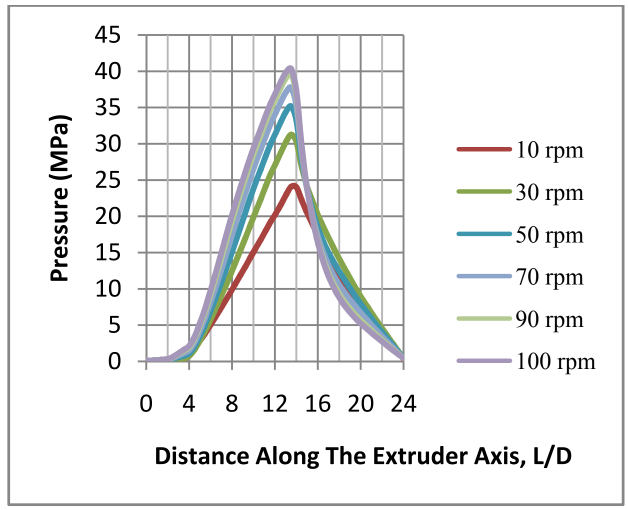

Fig. 9 Pressure profiles at different screw speeds for Rapid Compression Screw using 12 mm die.

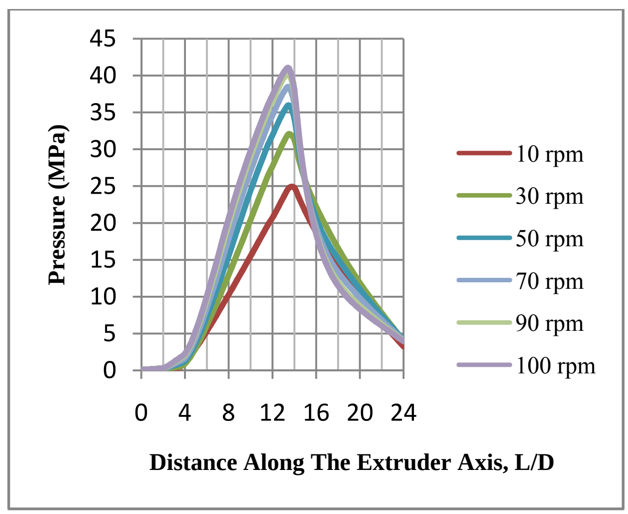

Fig. 10 Pressure profiles at different screw speeds for Rapid Compression Screw using 4 mm die.

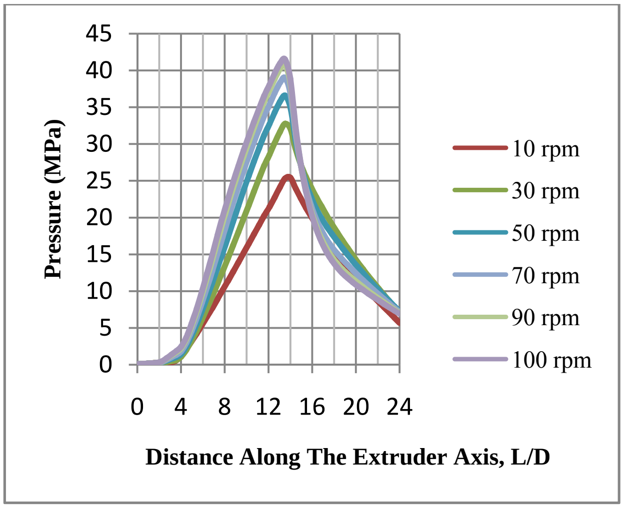

Fig. 11 Pressure profiles at different screw speeds for Rapid Compression Screw using 3 mm die.

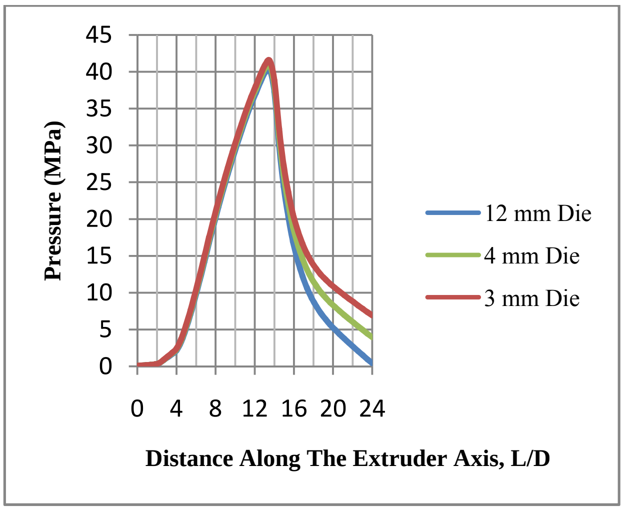

Fig. 12 Comparison between Different die diameters at 100 rpm for Rapid Compression Screw

Die (mm)	Maximum Pressure* (MPa)	Head Pressure (MPa)
12	40.32	0.35
4	40.96	3.21
3	41.51	5.66
*Maximum Pressure occurred at 13.5 Turns of screw		

Table.4 Values of Pressure for traditional screw at 100 rpm.

5. Conclusion

The results of simulating the proposed screw indicated that by means of changing the type of screw and changing the processing conditions, the axial pressure goes through maximum and minimum. The pressure profile along the length of the extruder reaches a maximum close to the end of the compression section of the screw. Sharp pressure peaks occurred at low speeds for the traditional screw case, while being at the high speed range for the rapid compression screw case. Different dies almost have no effect on pressure profile along the screw, but rather affect the head pressure.

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