

KINEMATICS OF SOLIDS CONVEYING

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Abstract

Solids conveying is typically calculated using friction factors. The friction factors depend on material and conditions, are difficult to measure, and the calculation is extremely sensitive to their value. Kinematic analysis of solids conveying is shown to yield the "solids lead angle" for the resin solids plug that does not require friction factors. Solids lead angle for different polymers are shown, and the data are used to make predictions of solids conveying performance without evaluation of friction factors.

Background

Numerous models [1-4] have been created and developed in order to accurately predict the performance of solids conveying in extrusion. All of the models commonly require accurate friction factor data for the screw surface and the barrel surface. Such data are generally not available, difficult to measure, and difficult to administer.

They are difficult to administer because they depend on barrel and screw surface temperatures, which are normally not accurately known. Surface temperatures also change greatly in the solids conveying region, and the value of it on the screw is rarely monitored. A coupled model [4] of solids conveying and surface temperature was attempted to overcome this problem, but the functional relationship of friction factors is very non linear and sometimes double valued. Any mathematical algorithm that depends on such functional relationships will be difficult to use.

The lead angle of the solids conveying has been shown [4] to be easily calculated by kinematic analysis from the screw dimensions, screw speed, flow rate, and bulk density of the polymer. Therefore, the data to calculate it are very easily obtained. Lead angles can then be collected for many conditions for correlation and predictions. Solids conveying lead angle then emerges as a different empirical constant with which to calculate solids flow instead of friction factors.

Solids Conveying Angle

The solids conveying lead angle is shown in Figure 1. It is defined as the angle that the motion of the solids feed plug makes with the vertical to the axial direction of the screw. For zero flow it is zero, and at maximum flow it is 90 degrees ($\pi/2$ radians.)

The solids conveying angle is shown [4] to be easily calculated from the kinematics of the solids conveying. It is given as

$$\phi = A \tan(v_z / \bar{R} \omega_p), \quad (1)$$

where axial velocity is given as

$$v_z = \frac{\dot{m} / \rho_B}{(2\pi\bar{R} - w_f / \sin(\theta))H}, \quad (2)$$

and solids plug rotational speed is given as

$$\omega_p = \omega - \frac{\dot{m} / \rho_B}{RHt_c}, \text{ rad/second} \quad (3)$$

where

$$\omega = 2\pi N. \quad (4)$$

Therefore, the solids conveying lead angle is given by the functional relationship of

$$\phi = f_1(\dot{m}, N, \rho_B, \bar{R}, H, t_c). \quad (5)$$

Flow rate is represented by the functional relationship of

$$\dot{m} = f_2(p, \bar{f}_B, \bar{f}_S, N, \bar{R}, H, t_c, w_f, L, \rho_B). \quad (6)$$

The average value of friction factors in Equation 6 is defined for the barrel, i=B, or for the screw, i=S as

$$\bar{f}_i = \frac{1}{L} \int_0^L f_{ff}(p, T_i, v, \text{polymer, surface}_i) dz. \quad (7)$$

Equations 6 and 7 are substituted into Equation 5 to give the solids conveying lead angle at the end of the solids conveying section, L, as

$$\phi_L = f_3(p_L, T_i, N, \bar{R}, H, t_c, w_f, \rho_B, L), \quad (8)$$

for a given polymer and surfaces.

Equation 8 shows the solids conveying lead angle, ϕ , to be given in terms of the independent process parameters and dimensions without explicitly involving friction factors. The effect of friction is not ignored, but implied through the independent variables that govern friction by Equation 7. The approach is now to experimentally determine the solids conveying angle and the level of dependence (or lack thereof) on the independent parameters of Equation 8.

Bulk Density

The only material property needed to calculate the solids lead angle is the bulk density. It is known to be a function of stress (pressure) and temperature. Fortunately, it can be easily and accurately measured, and values are

readily available [5] for many polymers. Values for a temperature of 25 °C are used with the assumption that the bulk temperature does not have time to increase substantially in the solids conveying portion of the extruder. The bulk density is assumed to be that for the pressure at the end of the solids conveying portion of the process.

Machine Data

Solids conveying flow rates were gathered for PET and PE from a variety of sources for different screws and machine sizes. Equation 1 was then used to calculate the prevailing solids lead angles. The screws were single stage, two-stage, and barrier types. Sizes ranged from 38 mm (1.5 inches) to 300 mm (12 inches.) The sources included lab tests, operational machines, and the literature. Therefore, this randomized sampling is assumed to be representative of solids conveying performance of operating machines.

PET and Two-Stage Screws: Figure 2 shows the solids lead angle for PET, in pellets or powder form, for a large range of screws sizes. All screws are two-stage devolatilizing screws. All the machines were operating well with the barrel zone near the melting point of the polymer, and all the screws had solids conveying section lengths of 9 to 10 L/D. The data indicate that for PET and a two-stage screw, that the average solids lead angle is 2.8 degrees. This held true for the PET as powder or pellets, screw diameters between 38 mm (1.5 inches) and 300 mm (12 inches), and a range of screw speeds between 30 rpm and 150 rpm. Screw helix angles were also between 16.3 degrees and 17.7 degrees.

All of the data gathered are for operational machines. Based on this, it is assumed that the solids conveying is stable and that the pressure developed is that needed for good melting. This means that the solids angle predicted by Equation 1 occurs at a nominal operating pressure, $p_{operating}$. Therefore, based on the results of Figure 2 for PET powder or pellets with a two-stage screw, Equation 8 can be reduced to

$$\phi_L = f_4(p_{operating}, T_{B-melting}, PET) = 2.8 \text{degrees} \quad (9)$$

PET with Barrier and Single-stage screws: Figure 3 shows the solid lead angles for barrier screws and PET in pellets or powder form. The diameters are 38 mm (1.5 inches) and 63.5 mm (2.5 inches.) The solids angle is shown to be an average of 4.5 degrees (vs. 2.8 degrees for two-stage) over most of the range of screw speeds. Therefore, screw type (i.e., barrier and single-stage vs. two-stage) is a factor in solids conveying angle for PET. This could be explained by the fact that barrier and single-stage screws normally offer less resistance to flow (lower pressure and more efficient melting) than the typical two-stage screw. Therefore, the solid lead angles for the

barrier and single-stage screws in Figure 3 are greater than those for the two-stage screws of Figure 2. Therefore, Equation 8 for PET and barrier screws is

$$\phi_L = f_5(p_{operating}, T_{B-melting}, PET) = 4.5 \text{degrees} \quad (10)$$

Screw speed below 25 rpm is a factor in Figure 3, whereas screw speed was not an influence for Figure 2 where speeds were greater than 30 rpm. It is likely that the assumption of the compact solids plug is not maintained at very low speeds. Therefore, all results should be interpreted for moderate or higher screw speeds.

Polyethylene for Barrier and Single-Stage Screws:

Figure 4 shows data [6] for four 88.9 mm (3.5 inches) barrier screws and two kinds of PE pellets, resin A (Dow 2045 A, LDPE) and resin B (Dow 133A, LLDPE). Data for LDPE resin C and a 63.5 mm (2.5 inches) single-stage extruder are also shown. All flow data are converted to the solids lead angle of Equation 1.

Figure 4 shows that the solids lead angle ranges between 5 and 8 degrees for the four 88.9 mm machines. The solids conveying lengths of the four screws were 4.5, 5, 6 and 6.5 L/D. Pressure near the end of the solids conveying section (9 L/D) was also provided with these data. Pressures varied between 4.9 MPa (710 psi) and 16.3 Mpa (2363 psi.) The scatter of these data indicate that L/D and pressure are likely factors that affect solids lead angle.

However, the solids lead angles are decidedly greater for the PE in Figure 4 than for the PET with barrier screws in Figure 3. Species of resin are then assumed an important factor in solids lead angle as would be expected by the inherent effect of friction coefficients.

Figures 2 to 4 are plots of solids conveying lead angle made without regard to the influence of pressure, which was satisfactory for most cases except Figure 4. It was assumed that the machines were functioning well so that the pressure at the end of the solids conveying would be a nominal value that is needed for melting and flow through the rest of the extruder. Hence, the pressure at the end of the solids conveying is assumed to not vary enough for a particular screw type to cause a noticeable variation in solids lead angle. However, pressure needs to be considered.

Laboratory Data

Precise data of flow versus pressure for solids conveying of LDPE are given [7] that are measured with a specially made isolated solids conveying section of screw and barrel with a load cell at the exit to measure pressure. The diameter is 63.5 mm (2.5 inches) and the L/D is 4.5, which includes 1.5 D for the feed opening. Two screw sections are used with channel depths of 8.89 mm (0.35 inch) and 11.1 mm (0.437 inch.) The test device provided

for controlled barrel and screw temperatures. The screws were operated at 50 rpm and 80 rpm for different barrel and screw temperatures. Data for flow rate vs. pressure are the results given. Data for the bulk density vs. pressure are also given.

These data of flow vs. pressure are used with Equation 1 to calculate the solids lead angle vs. pressure for barrel temperatures of 100 °C and 125 °C and screw temperatures of 50 °C and 100 °C. The results are shown in Figure 5.

Figure 5 shows that the higher pressure decreases the solids lead angle for the PE from up to 25 degrees at zero exit pressure to about 7 degrees and the highest pressure.

Figure 5 shows that channel depth and speed had little significant effect on the solids conveying angle. However, the data are significantly affected by the barrel zone and screw temperatures. The optimum pressure curve exists for 125 °C barrel and 50 °C screw. This is a barrel temperature near the melting point, which is typically recommended for good solids conveying for any polymer. The poorest pressure development occurred for the barrel temperature of 100 °C and screw temperature of 100 °C. Therefore, for this LDPE and L/D of 4.5, Equation 8 can be reduced to

$$\phi_L = f_4(p, T_B, T_S) \quad (11)$$

Linear regression in Figure 5 clearly demonstrates the effect of barrel temperature. The higher barrel temperature (125 °C, curves A and B) had the larger solids lead angle as compared to the 100 °C barrel (curves C and D.) However, extrapolation of the curves shows that the 100 °C barrel to have a tendency to produce higher pressures at low solids lead angle (low rate) than the 125 °C barrel. On the other hand, a hotter screw (100 °C vs. 50 °C) lowers the output pressure for either given barrel temperature.

Figure 5 shows that a solids lead angle of about 7 degrees will provide nominally optimum pressure for screw designs for this LDPE. This is shown to be independent of screw speed and channel depth of the solids sections, and it is at a point where barrel temperature effects coincide. If the assumption that the independence on diameter and lead length is also followed for LDPE as was the case for Figures 2 to 4, then these results could be used for screws of diameters other than 63.5 mm (2.5 inches) and with slightly different helix angles. The solids lead angle of 7 degrees was also typical of the operational machines for PE of Figure 4.

Summary

Solids conveying is described by the solids conveying lead angle. It can be easily calculated from kinematics of the screw and the resin bulk density [4].

The solids conveying angle can be used to characterize solids conveying in lieu of barrel and screw friction factors. Data for PET and LDPE were used to demonstrate that their solids angle is independent of

- screw diameter,
- screw speed,
- channel depth, and
- lead length.

Data for LDPE were used to show that the most significant factors are

- the pressure and
- the temperatures of the barrel and screw.

A linear correlation of solids lead angle to pressure for constant barrel and screw temperatures is shown to be a good approximation to solids conveying angle vs. pressure of LDPE. However, L/D of the solids conveying section is another factor that must be considered, but not included here.

Nomenclature

\bar{f}_i	average friction factor: barrel, i=B, or screw, i=S
H	channel depth
L	solids conveying section length
\dot{m}	flow rate
N	screw speed, rpm
p	pressure
R	radius to center of the channel
t_c	channel width in axial direction
T_i	temperature of barrel, i=B, or screw, i=S
v	velocity
v_z	axial resin velocity
w_f	flight width
z	axial direction
ϕ	solids lead angle
θ	screw helix angle
ρ_B	bulk density
ω	rotational speed, rad/sec
ω_p	solid plug rotational speed, rad/sec

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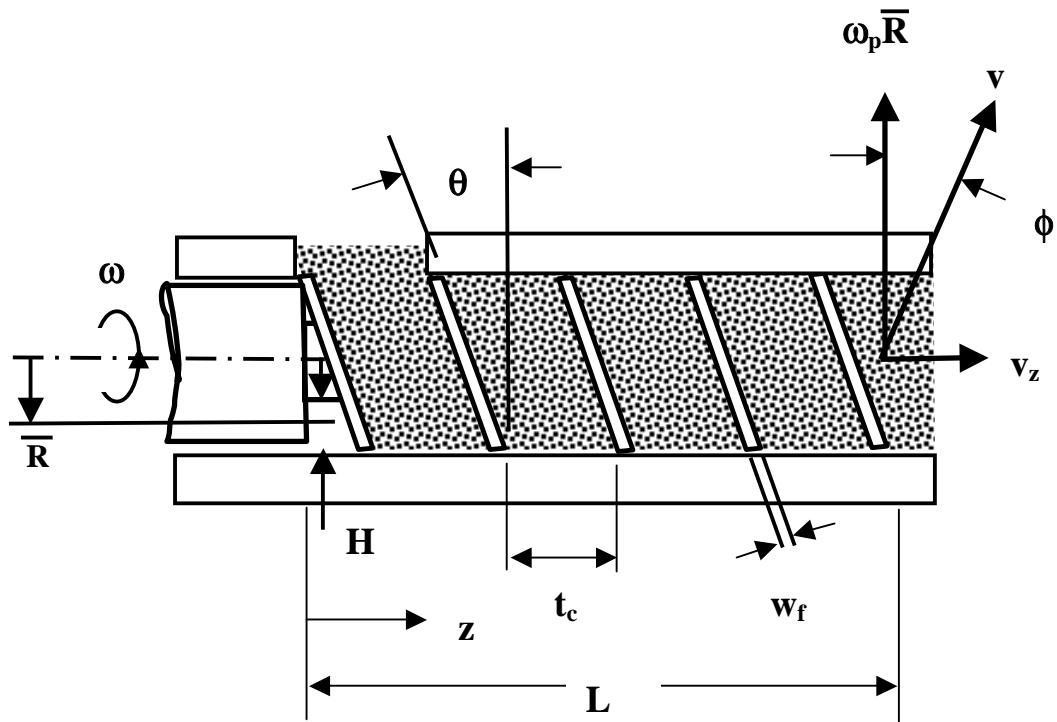


Figure 1. Solids Conveying Lead Angle, ϕ . The lead angle is defined at the end of the solids conveying section, L .

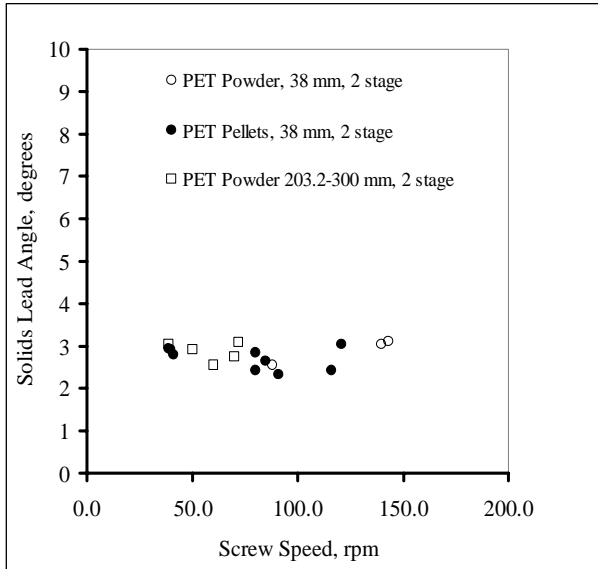


Figure 2. Solids Lead Angle for PET in Two-Stage Extrusion. Pellets or Powder used. All machines in stable operation. Barrel zones in solids conveying section near to melting point of PET.

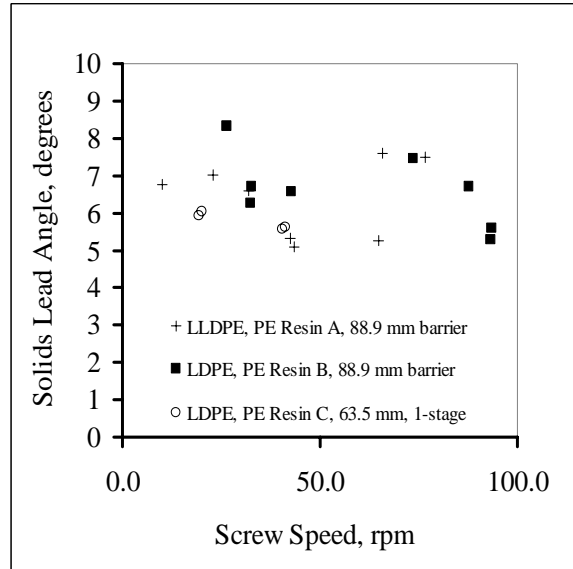


Figure 4. Solids Lead Angle for four Barrier Screws and a Single-Stage Screw for PE. The solids conveying sections for the four larger screws are 4.5, 5.0, 6.0, and 6.5 L/D

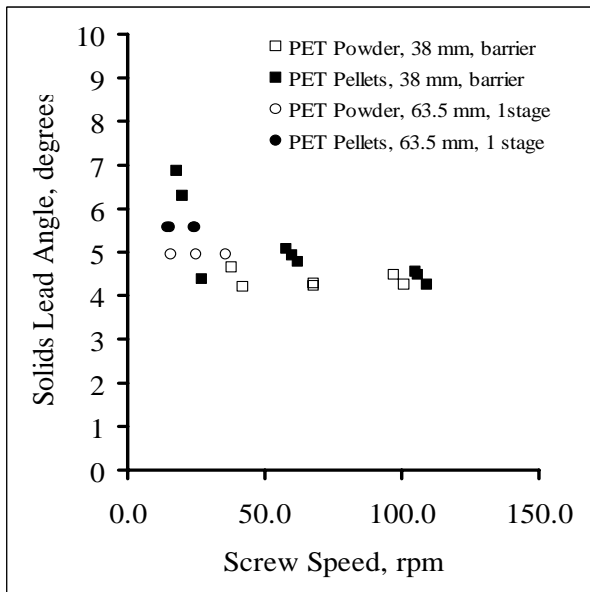


Figure 3. Solids Lead Angle for PET for a Barrier Screw and a Single-Stage Screw. Pellets or powder resins used.

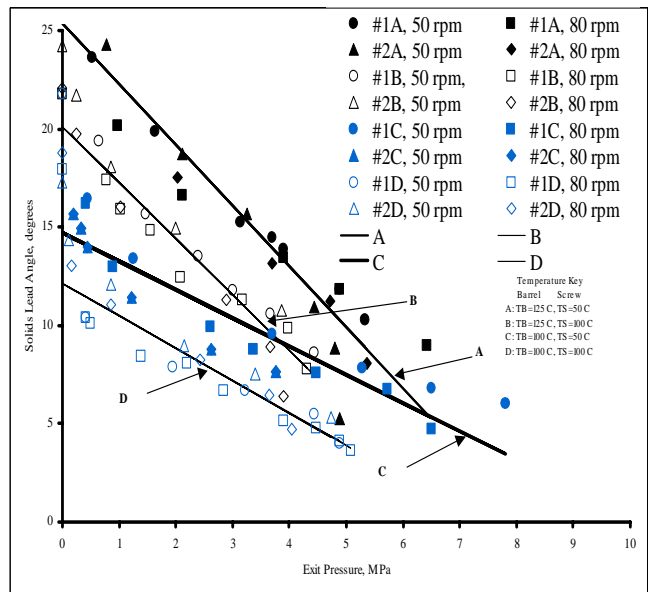


Figure 5. Solids Conveying Lead Angle vs. Pressure for LDPE. Test section of 63.5 mm diameter, 4.5 L/D. Screw #1 channel of 8.89 mm and screw #2 channel of 11.1 mm depth. Lines are regression for four combinations of barrel and screw temperatures.

Key Words: Extrusion, Calculating Solids Conveying, Solids Feed, Polyethylene, and Single-Screw Extrusion