KINEMATICS MODEL OF SOLIDS CONVEYING OF LDPE WITH A GROOVED BARREL

Stephen J. Derezinski, Extruder Tech, Inc., Penfield, NY 14526

Abstract

The kinematics model and solids conveying angle approach are used to analyze and calculate the solids conveying flow of LDPE with a grooved barrel. The result is an excellent prediction of solids conveying flow versus pressure for a grooved barrel extruder that does not require knowledge of friction factors.

Introduction

Predicting solids flow for a grooved barrel extruder with the classic definition of sliding friction of resin solids on the barrel is complex. A barrel friction factor modified to account for the presence of barrel grooves has been developed by Potente [1] as shown by Stevens and Covas [2.] The result is an equation for a modified barrel friction-factor that includes grooved geometry, and good results are reported. However, no actual examples of the calculated flow or supporting data are given [2.]

A discussion of grooved barrel solids conveying by Rauwendaal [4] indicates that excessive heating and temperature rise results from grooved-barrel conveying, and pressures as high as 300 MPa have been realized. A mathematical analysis of helical groove performance with friction coefficients that leads to an optimum barrel groove helix is then developed. However, the analysis does not include the thermal effects, and no data are used to demonstrate the level of accuracy of the calculations.

The kinematics model with the solids conveying angle (see Figure 1) as the empirical factor without the use of friction factors was recently developed [5.] In subsequent work this approach has been shown to robustly and accurately predict solids conveying flow versus pressure specifically for LDPE for smooth barrels [6.] The same approach is now applied to the solids conveying flow of LDPE with a grooved barrel. The result is a method for calculating the solids flow in a grooved-barrel extruder *that does not require the knowledge of friction factors*. Instead, the solids conveying angle is used as the governing empirical factor.

Determining the Solids Conveying Angle

From extrusion data of flow versus pressure, the solids conveying angle, ϕ, as a function of pressure can be calculated with the model [6] as follows.

$$\phi(p) = a\tan(N_Q \tan\theta / (1 - N_Q)) , \tag{1}$$

where dimensionless flow rate, N_Q, is a function of pressure.

$$N_Q = \dot{m}(p) / (\rho_B(p)\omega\overline{R}Ht_c), \tag{2}$$

and screw helix angle, θ, is

$$\theta = a\tan(t / (2\pi\overline{R})) . \tag{3}$$

The bulk density, kg/cu-m, of the LDPE polymer feed at 25 ^{o}C is also a function of pressure, MPa, as given by

$$\rho_B(p) = -2.04p^2 + 47.2p + 593.0 . \tag{4}$$

Data for flow rate at a given pressure are used to evaluate Equations 2 and 4, and Equations 2-4 are then used in Equation 1 to provide the solids conveying angle at the given pressure. Data for flow versus pressure are then used to develop the function of solids conveying angle versus pressure.

Flow Versus Pressure Data

Spalding, Hyun, and Hoffman [7] made careful laboratory measurements of solids conveying flow of LDPE as a function of pressure with a grooved barrel. Their experimental extruder was 63.5 mm in diameter with an L/D of 4.5. The device only contained a solids conveying section of a screw (fixed channel depth,) and a load cell indicated the pressure developed at the exit. The barrel temperature and screw temperature were controlled and measured. Two screw channel depths , 8.89 mm and 11.1 mm, were used. Two screw speeds of 50 rpm and 80 rpm were reported.

There were 8 equally spaced grooves in the barrel. Each groove width was 2.5 mm and each groove depth was 2.1 mm at the entrance. The depth of the grooves was tapered to zero by the end of the enclosed portion of the barrel, 3 L/D. The grooves were parallel to the barrel axis (not helical.) Flow rate as a function of pressure was reported for the combinations of two channel depths, two screw speeds, and temperatures.

Solids Conveying Angle Results from Data

The data for LDPE in the grooved-barrel experimental extruder [7] is now used to calculate the solids angle of LDPE according to Equations 1-4. Barrel temperatures of 125 ^{o}C, 100 ^{o}C, 75 ^{o}C, and 50 ^{o}C were combined with screw temperatures of 100 ^{o}C and 50 ^{o}C for the study.

Figure 2 shows the calculated results for solids conveying angle, ϕ, as a function of the ratio of exit to inlet pressure, p/p_0, for a grooved-barrel temperature of 125 °C. Two sets of data are shown in Figure 2, one for screw temperature of 50 °C and one for a screw temperature of 100 °C. The data for the grooved-barrel solids conveying angle does not have a significant dependence on screw speed and channel depth, so no distinction in the data is made for channel depth or screw speed. This was the same result for the smooth barrel solids conveying angle results [6.]

The solids conveying angle versus pressure ratio for each screw temperature of Figure 2 is determined by regression to be well approximated by a logarithmic function of the form

$$\phi(p) = A\ln(p/p_0) + B\,, \tag{5}$$

and the curves are plotted with the data in Figure 2 for each screw temperature. Coincidentally, the dependence of the solids angle on a logarithmic function of the pressure ratio is also found in the classic model with friction factors of Tadmor and Klein [3.]

Figure 3 shows similar results for a colder barrel of 100 °C. Again, the screw temperature is the discriminating factor that separates the data, and the data indicate that screw speed and channel depth are not significant factors. The data for the solids conveying angle for this barrel temperature follows the same logarithmic function as for the previous warmer barrel of 125 °C. Also, the solids conveying angles at a barrel temperature of 100 °C are generally lower than the solids conveying angles at a barrel temperature of 125 °C.

Bimodal Solids Conveying Angle

Figure 4 shows the solids conveying angle for a barrel temperature of 75 °C and 50 °C combined with screw temperatures of 100 °C and 50 °C. Figure 4 shows that the data fall into two distinct patterns of relatively high solids conveying angles and one of lower solids conveying angles, and data from either barrel temperature is found in each pattern, but the data for the screw temperature of 100 °C is only found in the lower mode. This indicates that the solids conveying angle at the screw temperatures of 50 °C is bimodal in nature. Therefore, the solids conveying angle is not uniquely predictable at screw temperatures of 50 °C. However, the logarithmic function is still seen to be appropriate to describe either mode of solids conveying angle versus pressure.

Equation for Solids Conveying Flow of LDPE

Equations 1 and 2 can be rearranged to calculate the flow as a function of solids conveying angle [6.]

$$\dot{m} = \rho_B(p)\omega\bar{R}Ht_c\,\frac{\tan\phi}{\tan\theta + \tan\phi}, \tag{6}$$

Equation 5 gives the solids conveying angle as a function of pressure, and it is combined with Equation 6 to model the solids flow as a function of pressure.

$$\dot{m} = \rho_B(p)\omega\bar{R}Ht_c\,\frac{\tan(A\ln(p/p_0)+B)}{\tan\theta + \tan(A\ln(p/p_0)+B)}, \tag{7}$$

Coefficients A and B are functions only of screw temperature and barrel temperature.

Calculated Flow versus Data

The model given by Equation 7 is compared to the original flow rate data to demonstrate the accuracy of the assumed logarithmic regression of the solids angle versus pressure. Figures 5 to 8 show the results for flow versus pressure for four different combinations of barrel and screw temperatures. Flow data for the different speeds and channel depths are presented in each figure. The curves that represent model according to Equation 7 for the same channel depths and speeds demonstrate how well the model, Equation 7, accommodates these factors.

Extrapolation of the Solids Angle Function

Figure 9 shows the extrapolation of the logarithmic function (Equation 5) for solids conveying angle versus pressure for the three barrel temperatures and two screw temperatures. The functions show a maximum pressure where the flow becomes zero, and it falls in a range of pressure ratios of 250 to 700 (25 Mpa to 70 Mpa.) The maximum pressures are much higher for this grooved barrel extruder than what was shown for a smooth barrel extruder [6.] This coincides with common knowledge [4] of the high pressures attainable with grooved barrel solids conveying as compared to smooth barrel solids conveying.

The extrapolated curves of Figure 9 follow a very orderly pattern. Solids conveying angles are highest for the highest barrel temperature (125 °C) and decrease with decreasing barrel temperature (100 °C and 50 °C). Each barrel temperature is shown for a pair of screw temperatures (100 °C and 50°C) and the solids angle for the hotter screw temperature (100 °C) is initially lower than that for the colder screw temperature (50°C.) At some point of pressure ratio, the curve for the hotter screw temperature is shown to cross that for the colder screw temperature, and this occurs in a very similar way for each pair of curves for the three barrel temperatures. The relative orderly pattern that results was unexpected, and it provides confidence that the logarithmic regression of the data is a sound assumption within the range of the data (pressures less than 10 MPa.)

Conclusions

1. The kinematics model with the solids conveying angle can be used to calculate the solids conveying flow of LDPE for grooved barrel extruders, and it does not require the use of friction factors.
2. The solids conveying angle is well approximated by a logarithmic function of pressure when the barrel is grooved, and the function is primarily dependent on screw and barrel temperatures.
3. The solids conveying angle of LDPE for a grooved barrel exhibits bimodal characteristics at barrel temperatures of 50 °C and 75 °C with a screw temperature of 50 °C.

References

1. Potente, H., *Kunstst,*. **75**, 1985, p 439.
2. Stevens, M. J. and J. A. Covas, *Extruder Principles and Operation,* Chapman and Hall, 1995, p 210.
3. Tadmor, Z and I. Klein, *Engineering Principles of Plasticating Extrusion,* Van Nostrand Reinhold Company, 1970, Chapter 4.
4. Rauwendaal, Chris, *Polymer Extrusion,* Hanser Publishers, 1990, pp 246-256.
5. Derezinski, S. J., "Kinematics of Solids Conveying," *Conference Proceedings, ANTEC 2003,* Society of Plastic Engineers, 2003, pp. 218-222.
6. Derezinski, S. J., "Kinematics Model of Solids Conveying of LDPE," *Conference Proceedings ANTEC 2004,* Society of Plastic Engineers, 2004, pp. 148-153.
7. Spalding, M. A., K. S. Hyun and R. Hoffmann, "An Experimental Investigation of Solids Conveying in Smooth and Grooved Barrel Single-Screw Plasticating Extruders," *Conference Proceedings, ANTEC '98,* Society of Plastic Engineers, 1998, pp. 136-141.

Nomenclature

A	constant
B	constant
H	channel depth
$\dot{m}$	flow rate
N	screw speed, rpm
p	exit pressure
p_0	inlet pressure
$\bar{R}$	radius to center of the channel
t	lead length
t_c	channel width in axial direction
T_i	temperature: barrel, i=B, or screw, i=S
ϕ	solids conveying angle
θ	screw helix angle
ρ_B	bulk density
ω	rotational speed, rad/sec

Key Words

Solids, conveying angle, conveying, feed, single screw, feeding, extrusion screw, extrusion calculation, flow, solids flow, flow calculation, extrusion analysis, grooved barrel, model

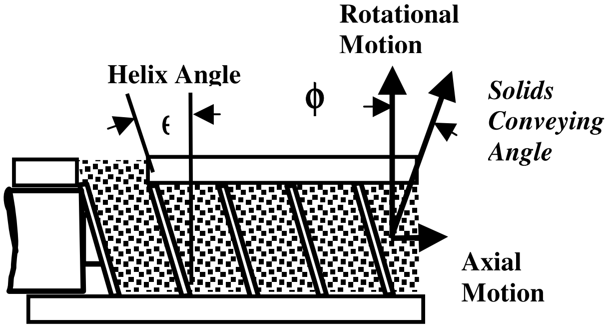

Figure 1. The definition of the solids conveying angle, ϕ, for solids flow in an extruder

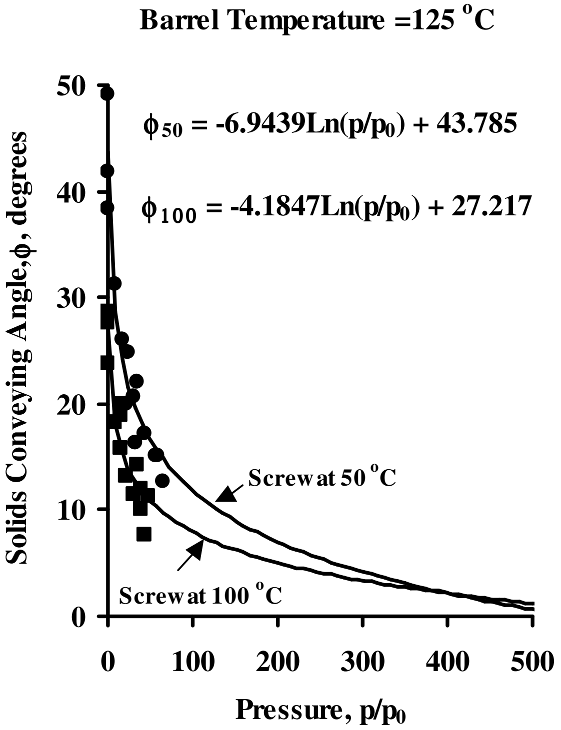

Figure 2. Solids Conveying Angle versus pressure for 125 °C Barrel Temperature The lines are logarithmic regression with the equations shown for each of two screw temperatures.

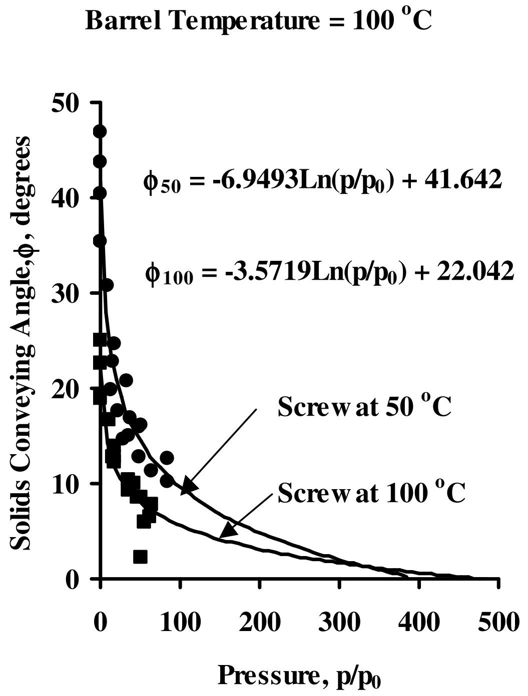

Figure 3. The Solids Conveying Angle for a Barrel Temperature of 100 °C The lines are logarithmic regression, and the equations are shown for each of two screw temperatures.

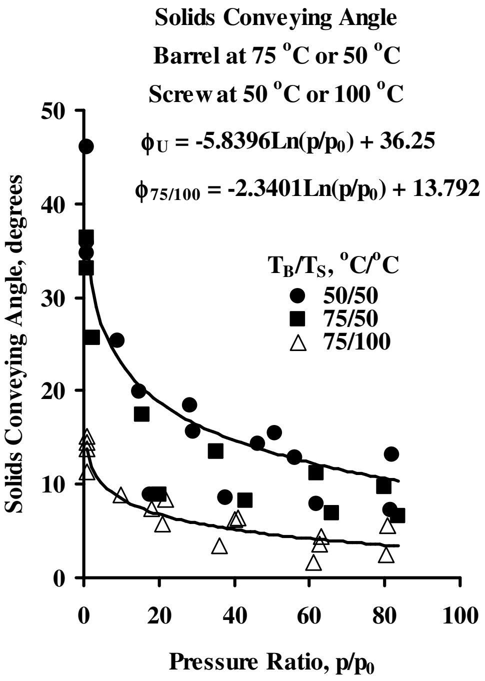

Figure 4. Data for Solids Angle vs Pressure for Barrel at 75 °C or 50 °C and the Screw at 50 °C or 100 °C The data appear to be bimodal.

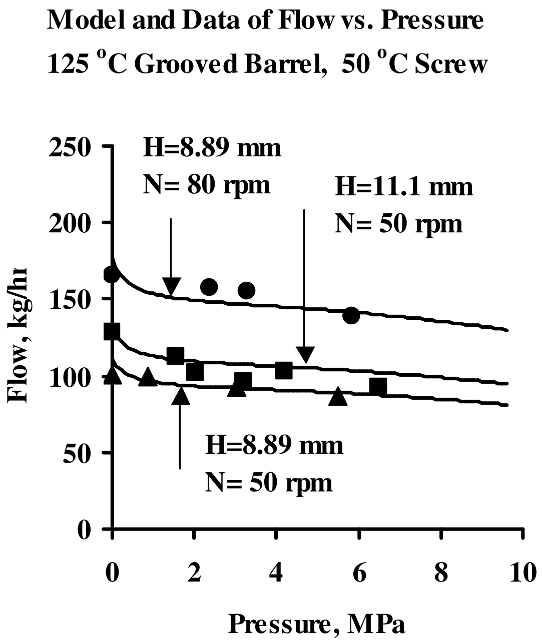

Figure 5. Flow Rate vs Pressure for Barrel at 125 °C and the Screw at 50 °C The lines represent the model predictions.

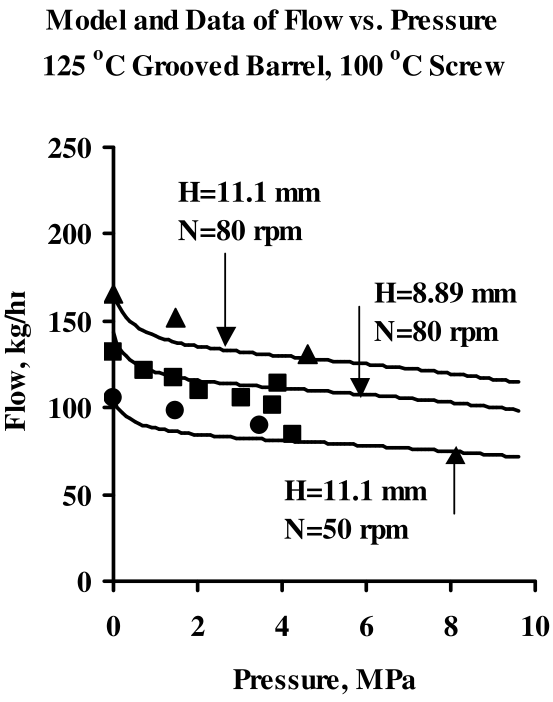

Figure 6. Flow Rate vs Pressure for Barrel at 125 °C and the Screw at 100 °C The lines represent the model predictions.

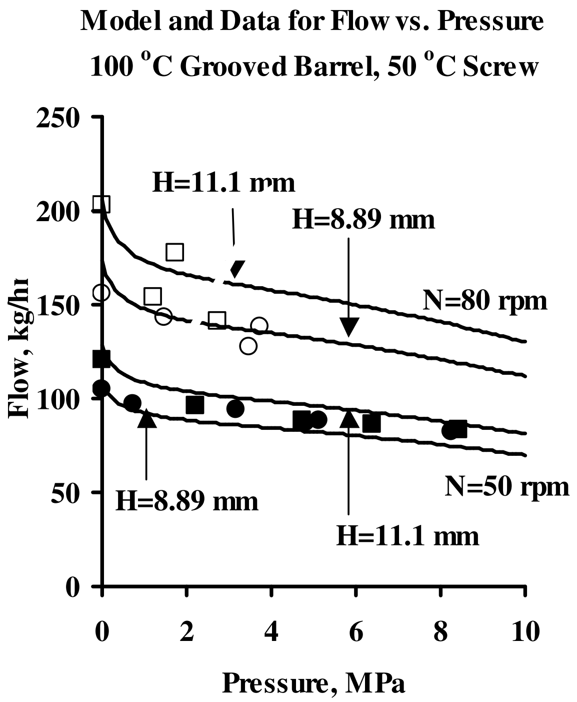

Figure 7. Flow Rate vs Pressure for Barrel at 100 °C and the Screw at 50 °C The lines represent the model predictions.

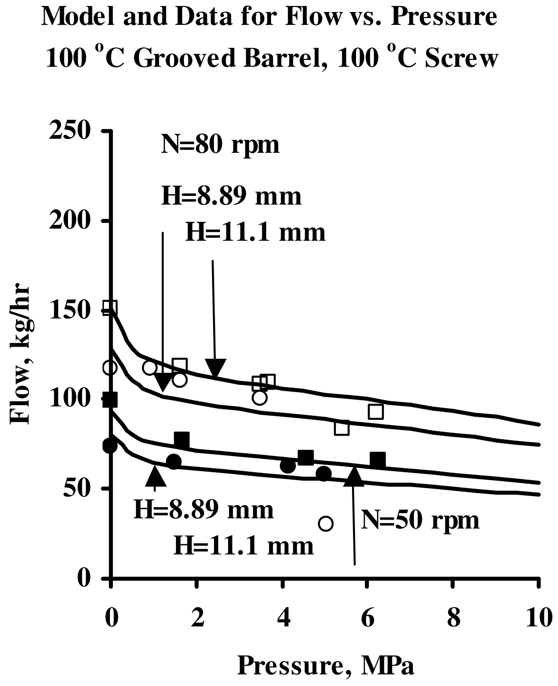

Figure 8. Flow Rate vs Pressure for Barrel at 100 °C and the Screw at 100 °C The lines represent the model prediction.

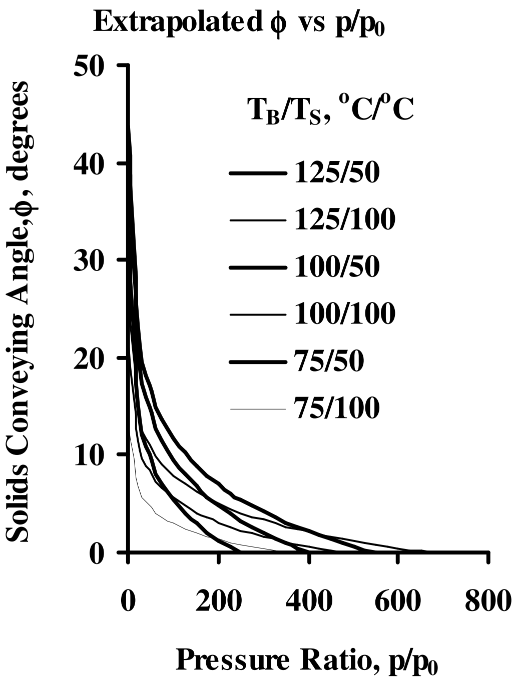

Figure 9. The Extrapolated Functions for Solids Conveying Angle vs Pressure A very regular pattern is observed over the extended pressure domain.