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Flow Surging in Single-Screw, Plasticating Extruders

Mark A. Spalding, Joseph R. Powers, Phillip A. Wagner, and Kun Sup Hyun - Dow Plastics, Midland, MI

Abstract

Flow surging in single-screw, plasticating extruders is the variation of the machine's rate with time, and it generally leads to higher production costs, lost production, and often higher scrap rates. Flow surging can originate from many different sources including machine controls, resin feedstock variation, screw geometry, and machine temperature. This paper will focus on flow surging that originates from improper solids conveying, and it will present experimental data and corrective action to eliminate or minimize surging.

Introduction

Flow surging is defined as the oscillatory change in the output rate of the extruder while maintaining constant set point conditions. Flow surging can originate from many different sources including improper solids conveying, melting instabilities, and improper control algorithms (1-5). Surging in most case results in lower production rates, higher scrap rates, material degradation, and higher labor costs.

Previous work documented a severe and random flow surging problem due to improper solids conveying and a solids obstruction upstream of a spiral dam (4). These surging problems resulted in severe pressure fluctuations at the discharge of the extruder and thus large rate surges at the die. Rate surges at the die can be estimated from the pressure surges using the following for flow through a cylindrical restriction (or die) (4):

$$\Delta Q = (Q_1 - Q_2) / Q_1 = 1 - (1 - \Delta P)^{1/n} \qquad (1)$$

$$\Delta P = (P_1 - P_2) / P_1 \qquad (2)$$

where n is the power law index, Q1 and P1 are the rate and discharge pressure at condition 1, and Q2 and P2 are the rate and pressure at condition 2. For example, a 5% variation in the discharge pressure (ÄP = 0.05) for a polymer with a power law index of 0.3 will cause a 16% change in the instantaneous rate (ÄQ=0.16). An instantaneous rate change of this magnitude is unacceptable for most processors.

Solids conveying depends on a balance of forwarding forces at the barrel wall and pushing flight and retarding forces at the screw surface (6). These forces depend mainly on the geometry of the channel and are directly proportional to the coefficient of dynamic friction for temperatures less than the melting or devitrification temperature and on viscous forces for higher temperatures (7). Since the coefficient depends on temperature, pressure, and velocity (8), surface temperature changes for the barrel and screw in the feeding section will strongly affect the performance of the extruder. If the surface temperatures become too different from the optimal values, flow surging and loss of rate will occur.

Improper design and operation of the melting section of the screw can both lead to extrusion instabilities. For example, solid bed break up (3) can cause solids to migrate downstream. These solids can wedge into other sections of the screw and cause the extruder to flow surge (2,4) or cause the extrudate to have periodic changes in temperature. Periodic changes in discharge temperature will cause some level of flow surging at the die (9).

The goal of this work is to describe the thermal effects of solids conveying on flow surging using two examples for a high impact polystyrene (HIPS) resin.

Materials
Rheology, bulk density, coefficient of dynamic friction, and the shear stress at the polymer metal interface were measured for the HIPS resin. The rheology and bulk density of the resin were essentially the same as that previously reported for a slightly different HIPS resin (10,11). The shear stress at the polymer-metal interface is reported here rather than the dynamic friction since friction is only defined for solid-state processes, while the stress can be described from ambient temperatures up to processing temperatures. The shear stress at the interface (12) for HIPS resin is shown by Figure 1 at a pressure of 0.69 MPa. As indicated by this figure, the shear stress was nearly constant from ambient temperature up to about 110°C, increased to a maximum stress near 150°C, and then decreased as the temperature was increased further. Optima! performance of the solids conveying section for this resin would be such that the forwarding forces are maximized with metal surface temperatures near 150°C where the stress is a maximum, and the retarding forces minimized with metal surface temperatures of 110°C or lower. Thus, optimal solids conveying for HIPS would occur with a feed zone barrel inner surface temperature near 150°C and a screw surface temperature in the feed section no higher than 110°C. In practice, screw temperatures less than 90 or 100°C are preferred such that melting of the resin does not occur if an emergency shutdown should occur. For the solid state temperature region, the shear stress at the interface can be converted to the coefficient of dynamic friction by the following (12):

$$f = \hat{o}/P$$

where f is the coefficient of dynamic friction, $\hat{o}$ is the shear stress at the polymer metal interface, and P is the pressure (0.69 MPa).

Screw Temperature Control
A severe and random flow surging problem limited the production rate for a large-diameter, two-stage, vented extruder. if it were not for a gear pump positioned between the extruder and die, this extrusion line would not be operable. The surging did, however, limit the output of the line to about 60% of its potential rate. The maximum potential rate is the rate that the extruder can run at high screw speed and with proper operation. In order to diagnose the problem, a data acquisition system was temporarily connected to the extrusion panel. The screw was single-flighted and typical of what is used for HIPS resins. Screw temperature control was accomplished by flowing cooling water through a rotary union into and out of a hole cut into the feed end of the screw (13). This hole extended to about 4 diameters into the feed section. Pressure sensors were positioned in the barrel wall at the end of the first-stage transition section (P1), at the end of the first-stage metering section just before the vent (P2), and at the discharge. An additional pressure sensor was positioned at the inlet (suction side) to the gear pump. A temperature sensor was positioned in the transfer line upstream of the gear pump to measure extrudate temperature. A commercial control scheme adjusted the screw speed to maintain a constant pressure of 9 MPa to the inlet of the gear pump. The gear pump was operated at constant speed in order to maintain a constant flow rate of material to the downstream equipment.

Steady-state operation of the extruder is shown by the first 400 minutes in Figures 2, 3, and 4. The data for these figures were from the same experimental run. At these conditions, the extruder was operating at about 70% of its potential maximum rate and the screw speed varied only about ± 2 rpm. The barrel pressure at the end of the first-stage transition section, P1, had variations of about ± 3 MPa about the average pressure. This pressure variation was considerably higher than was expected and suggests that the extruder, although running stable, was on the verge of unstable operation. Some of the variation was due to the movement of the flight tip past the sensor. Barrel zone temperatures tracked the set point values and were stable. Calculations indicated that the first stage was full of resin.

At about 410 minutes into the run, the extruder started to operate unstably, as indicated by Figures 2, 3, and 4. The processing change that caused the extruder to go from a stable operation to an unstable one is not known, but it could have been due to minor changes in the bulk density of the feedstock or cooling water fluctuations. As indicated by these figures, the event started when the P1 pressure decreased slightly, causing the rate and the P2 pressure to decrease. This decreased pressure transmitted down the extrusion system, eventually decreasing the pressure at the inlet to the gear pump. To correct for the lower pressure, the controller on the gear pump increased the speed of me screw from 100 to about 160 rpm. Next the Pt pressure increased due to the higher screw speed and higher flow rate, as indicated by Figure 3. As the pressure increased at the gear pump inlet, the gear pump controller decreased the screw speed back to 100 rpm, causing the extruder to flow surge. Flow surging caused the screw speed controller to oscillate about once every 25 minutes. As indicated by Figure 2, the screw speed controller was able to provide a relatively stable pressure to the pump inlet, allowing the process to run at reduced rates. The barrel zone temperatures, as indicated by Figure 4, were extremely oscillatory.

As indicated by Figure 2, the P1 pressure was considerably lower during the period of unstable operation. This result indicates that the cause of the problem originated in the first stage of the screw before the metering section. At a screw speed of 160 rpm, the extruder was capable of a rate of at least 50% greater than the actual rate. This lower than expected rate indicated that the first-stage metering section was operating only partially filled. The most likely reason for a starved metering section was poor solids conveying from the feed section to the transition section. This poor solids conveying was likely due to improper temperature control of the metal surfaces in the feed section of the extruder and screw. Barrel feed zone heaters and controllers were examined and determined to be operating properly

at set point temperatures typically used for HIPS. Based on this information, the investigation was focused on screw temperature control.

The effect of internal screw cooling was determined during a period when the extruder was operating stably. For this stable extrusion period, cooling water was flowing to the screw-cooling lance and the extruder was operating stably and properly at a rate of 70% of its potential maximum. The metal surface temperatures of the pipes used to flow water into and out of the screw were measured at 29 and 37°C, respectively. At about 28 minutes into the run, the cooling water flow to the screw was turned off, as indicated by Figures 5 and 6. At about 30 minutes, the pressure at the end of the first-stage transition section, P1, started to decrease as shown by Figure 6, indicating that solids conveying was significantly reduced. Like before, the reduced solids flow caused the downstream pressures to decrease, and ultimately to cause the extruder to flow surge. At about 36 minutes into the run, cooling water flow was turned on and within about 4 minutes the extruder operation became stable, as indicated by the Figures 5 and 6. The surface temperature of the pipe for water flow out of the screw was measured at 81°C just after the cooling water was turned on; a temperature change of 44°C. Previous research on HWS (14) has shown that solids conveying becomes difficult or unstable at screw temperature of about 160°C and higher. The temperature of the screw surface was unknown, but it likely increased by at least 44°C and possibly approached 160°C.

Based on the above data, the cause of the extrusion instability was identified as high screw surface temperatures in the feed section. These high surface temperatures caused the coefficients of dynamic friction to increase, increasing the retarding forces on the solids at the screw surface. Since solids conveying depends on a combination of forwarding forces at the barrel wall and pushing flight and retarding forces at the screw root and trailing flight, an increase in the retarding forces will cause a reduction in the solids conveying rate. The instability appeared to be random due to the complicated interactions of cooling water flow rate and temperature, and changes in bulk density of the feedstock.

To increase the operating window for stable extrusion, the cooling level to the feed section of the screw was increased by lengthening the cooling hole in the screw. The cooling hole length was increased from 4 diameters into the flighted section to 7 diameters; i.e., up to the end of the feed section. After the screw modification, the extruder has not experienced instabilities of this type and the rate was increased to 100% of its maximum potential rate.

Feed Casing Temperature Control
On a different occasion, the same extruder started to flow surge, but with a slightly different frequency, as shown by Figures 7 and 8. As indicated by these figures, there were short time periods when the discharge pressure and screw speed were stable and the motor current was high. During these periods, the extruder was operating well but at a reduced production rate. During periods of unstable operation, the motor current decreased by about 20%. the screw speed increased, and the discharge pressure became extremely oscillatory. Like the previous case, as the motor current decreased solids conveying decreased, causing the controller to increase the speed of the screw.

During the trial, the feed casing to the extruder had an outside surface temperature of about 80°C. Although not measured, the inside cylinder wall of the feed casing for first 1.5 diameters downstream of the feed opening was considerably hotter. These higher temperatures were caused by a combination of frictional heating of the solids on the wall and also by conduction from the first heated zone of the barrel. It is estimated that temperatures as high as 170°C occurred in the feed casing. Optimal solids conveying will occur when the stress at the polymer-metal interface at the barrel is a maximum. This maximum stress occurs for HIPS at a surface temperature near 150°C, as indicated by Figure 1. Surface temperatures higher than 150°C in the feed section will reduce conveying and lead to starving of the screw channels and ultimately flow surging. Corrosion inside of the cooling channels of the feed casing prevented the flow of cooling water. Cleaning the cooling channels and adding a larger cooling water recirculation pump reduced the temperature of the feed casing and eliminated the flow surging problem.

Discussion

The examples presented show the effect of improper surface temperatures in the feed section of a plasticating extruder. Acceptable solids conveying will occur when the melting and metering sections are full of resin and under pressure; i.e., the first-stage metering section must control the rate. If the solids conveying section is rate controlling as in the two examples, then downstream sections of the screw channel will be starved leading to low rates, material degradation, and flow surging.

Optimal conveying forces occur when the forwarding forces are maximized and the retarding forces are minimized. The forwarding forces occur at the barrel-polymer interface and at the pushing flight, while the retarding forces occur at the screw root and the trailing side of the screw (6). These forces originate from solid-state friction at low temperature (7) and by viscous forces at higher temperatures (8,11). Both types of forces are proportional to shear stress between the rubbing polymer and the metal surface. For HIPS, this shear stress is shown by Figure 1. As indicated by this figure, the shear stress is relatively constant at temperatures less than 100°C, has a maximum stress at about 150°C, and then decreases with increasing temperature. In order to maximize the forwarding force at the barrel surface, it is

obvious from Figure 1 that the barrel surface temperature in the feed section should be about 150°C. In practice, an axial temperature gradient will exist between the water cooled feed casing and the first heated zone of the extruder barrel, and temperature sensors are generally not capable of measuring the surface temperature of the barrel accurately (15). Thus, an experimentally determined first zone temperature in the range of 150 to l70°C and a feed casing temperature around 35 to 45°C is acceptable. For the screw, both forwarding and retarding forces occur, yet the temperature of the screw surfaces must be controlled to the same temperature. Experience has shown that optimal screw temperatures for HIPS are those less than 90°C. For a temperature range of ambient up to 90°C, the retarding forces are essential the same, and by reducing the temperature below the glass transition temperature, devitrification (melting) will not occur on the screw root during an emergency shutdown.

Conclusions

Transient process data clearly show the effects of feed zone temperature control on the extrusion performance of HIPS. Optimal feed zone barrel and screw temperature control must ensure that the solids conveying section delivers adequate resin to keep the downstream sections of the first stage full. The optimal temperatures maximized the solids conveying forwarding forces and minimized the retarding forces.

References

1. Z. Tadmor and I. Klein, "Engineering Principles of Plasticating Extrusion," Van Nostrand Reinhold Co., New York, 1970.
2. I. Klein, SPE J., 28, 47 (1972).
3. R.T. Fenner, A.P.D. Cox, D.P. Isherwood, SPE ANTEC Tech. Papers, 24,494 (1978).
4. K.S. Hyun and M.A. Spalding, Adv. Polym. Tech., 15, 29 (1996).
5. K.S. Hyun, M.A. Spalding, and J. Powers, Plast. Eng., 52, 4, 33 (1996).
6. K.S. Hyun and M.A. Spalding, SPE ANTEC Tech. Papers, 43, 211 (1997).
7. CI. Chung, SPE J., 26, 32 (1970).
8. M.A. Spalding, D.E. Kirkpatrick, and K.S. Hyun, Polym. Eng. Sci., 33,427 (1993).
9. J.R. Thompson, SPE ANTEC Tech. Papers, 40, 288 (1994).
10. J. Dooley, K.S. Hyun, and K. Hughes, Polym. Eng. Sci., 38,1060 (1998).
11. K.S. Hyun and M.A. Spalding, Polym. Eng. Sci., 30, 571 (1990).
12. M.A. Spalding, K.S. Hyun, and B.R. Cohen, SPE ANTEC Tech. Papers, 43, 202 (1997).
13.S.R. Jenkins, J.R. Powers, K.S. Hyun, and J.A. Naumovitz, J. Plastic Film and Sheeting, 6, 90 (1990).
14. M. Mizoguchi, Japan Steel Works Tech. News, 11, 1 (1975).
15. T.W. McCullough and M.A. Spalding, J. Reinforced Plast. Comp., 16, 1622 (1997).

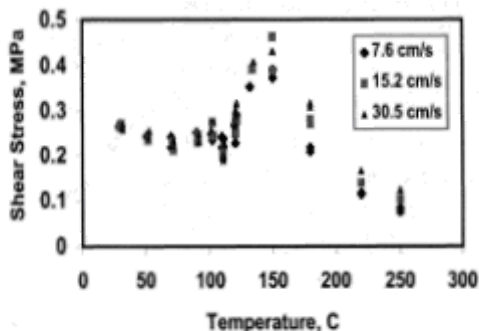Key Words: Flow Surging, Solids Conveying, Extrusion, HIPS.

Figure 1. Shear stress between HIPS and a metal surface at 0.69 MPa and as a function of sliding velocity.
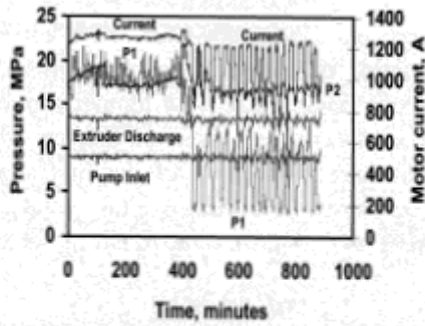
Figure 2. Barrel, discharge, and pump inlet pressures and motor current for stable and unstable extrusion for a large-diameter extruder running HIPS.
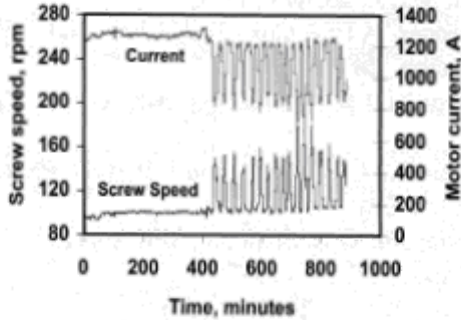

Figure 3. Screw speed and motor current for a large-diameter extruder running stable and unstable.
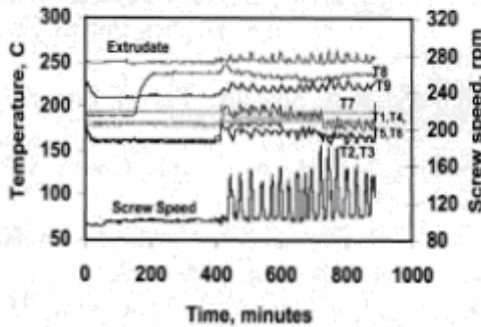

Figure 4. Screw speed, extrudate temperature, and barrel zone temperatures for a large-diameter extruder running stable and unstable.
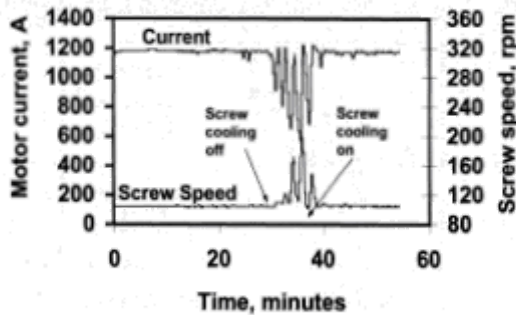

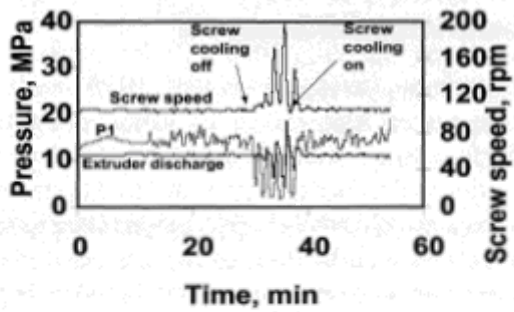Figure 5. Screw speed and motor current for the screw cooling experiment.

Figure 6. Screw speed, pressure at the entry to the first-stage meter (P1), and discharge pressure for the screw cooling experiment.
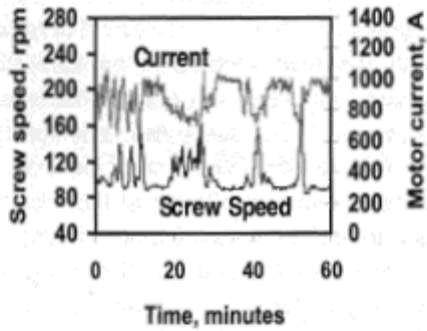

Figure 7. Screw speed and motor current for a large-diameter extruder with a feed casing that was too hot.
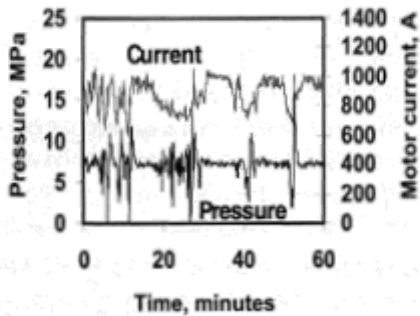

Figure 8. Discharge pressure and motor current for a large-diameter extruder with a feed casing that was too hot.

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