1999 Best Paper - The Effect of Flight Radii Size on the Performance of Single-Screw Extruders

The Effect of Flight Radii Size on the Performance of Single-Screw Extruders

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Abstract

The size of flight radii on the screw channel is important for the proper performance of a single-screw extruder. SPI guidelines state that the root radii should not be less than half the depth of the channel. Improper design or fabrication, however, often results in radii that are less than half that for the metering and transition sections, leading to regions with long residence time and material degradation. For optimal solids conveying, however, the effect of flight radii is considerably more complicated. This paper will present experimental and numerical data that indicate how to specify the flight radii for all sections of the screw.

Introduction

The proper design of a single-screw extruder screw must include channel depths, lead lengths, section lengths, and dimensions of specialized sections such as mixing devices. The specifications of the flight radii are commonly made using a combination of personal experience and guidelines (1) from The Society of the Plastics Industry, Inc. (SPI). These guidelines state "unless otherwise specified the root radius will not be less than ½ of the flight depth up to 25 mm radius." Often during the fabrication process, however, manufacturing errors result in flight radii that are less than that specified in the design.

For the solids conveying section, the effect of flight radii size is unknown. Most designers will use slightly smaller radii for the solids conveying section, typically about 1/2 to 1/4 the depth of the feed channel. The smaller radii are believed to increase solids conveying rates by increasing the cross-sectional area perpendicular to the flight tip.

Considerably more is known about the effect of the flight radii size for metering sections (2-4), mostly from numerical simulations. These simulations indicate that flows at the radii of a screw channel can be extremely low in both the cross-flow and downstream directions for channels with very small radii (2,3). These low flows lead to regions with very high residence times. If the residence time is long enough, material will degrade and eventually contaminate the extrudate (5). The magnitude of the flows in these regions, however, are considerably higher for channels with radii larger than the depth of the channel (4).

The goal of this work is to describe the effect of the flight radii size on the performance of the extruder. Experimental and numerical data will be shown for the effect of radii size for the solids conveying and metering sections.

MATERIAL

A low density polyethylene (LDPE) resin was used for the solids conveying study and the numerical simulations. The resin had a melt index (L) of 2.0 and a solid density of 0.922 g/cm3. Shear viscosity data (7), thermal properties (4), bulk density (6), lateral stress ratio (8), and the coefficients of dynamic friction (6) for the resin were presented earlier.

SOLIDS CONVEYING

The effect of flight radii size on solids conveying was determined using a device that measures solids conveying performance (6). The device was constructed from a 63.5 mm diameter extruder. The standard barrel was removed from the extruder and it was replaced with a short barrel, providing for a total length-to-diameter (LID) ratio of 4.5. A schematic of the device is shown by Figure 1. The feed hopper casing had an effective barrel length of 1.9 diameters and was water cooled. The removable barrel was 2.6 diameters in length and had a smooth bore. The feed opening was 1.5 diameters in length; the enclosed solids conveying length by the barrel and casing was 3 diameters. The barrel temperature was controlled using a single-zone, 2000 watt heater. The actual temperature of the barrel was measured using four strategically placed thermocouples at different axial positions.

Two screws with different flight radii size were used for this study; a small-radii and large-radii screw. Both screws were square-pitched, had flight widths perpendicular to the flights of 6.4 mm, flight clearances of 0.07 mm, and constant channel depths of 11.1 mm. The small-radii screw had pushing and trailing flight radii of 6 and 16 mm, respectively. The large-radii screw had radii of 19 mm for both the pushing and trailing flights. The shanks were bored for internal screw temperature control. The temperature of the screw was controlled by flowing pressurized heated water into the shank end of the screw using a rotary union assembly.

Pressure was applied to the discharge end of the device using a rotating torpedo positioned on a spindle, as shown by Figure 1.

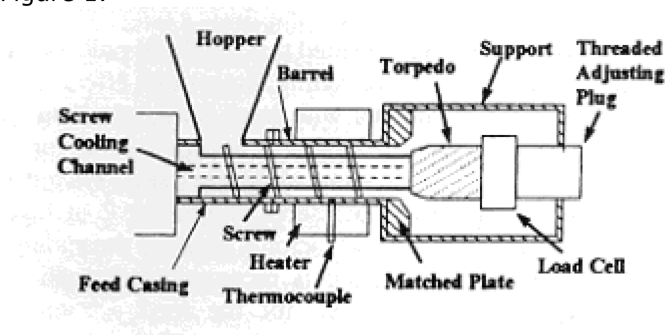

Figure 1. Schematic of the solids conveying device.

Figure 1

The gap between the torpedo and a matched plate attached to the barrel controlled the amount of pressure at the discharge end. Typically, a gap that was slightly larger than the diameter of the pellets permitted the material to discharge at zero pressure. The gap between the torpedo and the matched plate was set by adjusting the position of a threaded plug. The force generated was measured using a load cell positioned between the torpedo and the plug. Pressure at the discharge end of the device was calculated by dividing the force at the torpedo by the cross-sectional area of the annulus created by the screw root and the inside barrel diameter. The feed casing temperature was maintained at about 30°C using cooling water.

Solids conveying rates were measured as a function of discharge pressure at a screw speed of 50 rpm, a screw temperature of 50°C, and nominal barrel temperatures of 75, 100, and 125°C. At most conditions, the discharged pellets were essentially identical to those of the feed. At high discharge pressures and a barrel temperature of 125°C, however, some of the pellets were melted by the time they were discharged. As indicated by Figures 2, 3, and 4, the solids conveying rates were complicated functions of the barrel temperature, flight radii size, and discharge pressure; previous research showed that rates were also a function of screw speed, channel depth, barrel type (smooth or grooved), and screw temperature (9).

Figure 2 shows the conveying rates for both screws at a barrel temperature of 75°C.

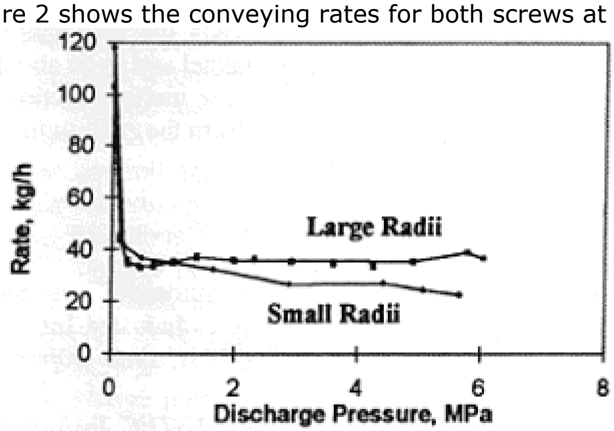

Figure 2. Solids conveying rates for a barrel temperature of 75°C, a screw temperature of 50°C, and 50 rpm.

Figure 2

At a discharge pressure of zero, the rates were 118 and 103 kg/h for the small-radii and large-radii screw, respectively, a decrease in rate of about 13% for the large-radii screw. This rate decrease is most likely due to the lower cross-sectional area available for conveying for the screw with the large radii. The cross-sectional areas of the channels perpendicular to the flights were calculated at 550 and 490 mm2 for the small-radii and large-radii screws, respectively, an area decrease of 11% for the large-radii screw. As the discharge pressure was increased to about 0.5 MPa, the rates decreased to about 37 and 34 kg/h for the small and large-radii screws, respectively, a rate decrease of about 8% for the large-radii screw. As the discharge pressure was increased further, the rate for the small-radii screw decreased nearly linearly to about 23 kg/h at 5.7 MPa. The rate for the large-radii screw, however, increased slightly to 37 kg/h as the pressure was increased to 1.4 MPa. For pressures between 1.4 and 6.0 MPa, the rates were essentially constant at about 37 kg/h for the large-radii screw. This was the first time that a rate increase with increasing pressure was observed for this solids conveying device.

Similar solids conveying rate data were observed for a barrel temperature of 100°C, as shown by Figure 3.

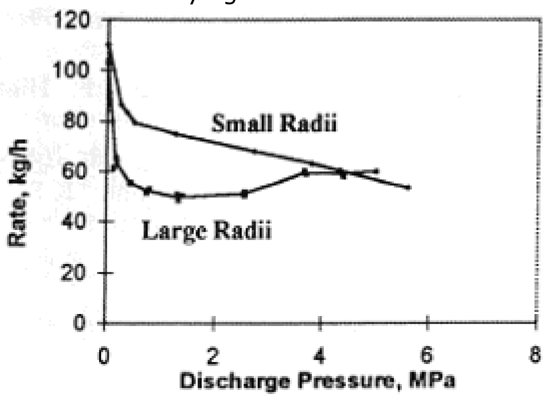

Figure 3

As indicated by this figure, the rates were 110 and 103 kg/h for the small and large-radii screws, respectively, a decrease of about 6% for the large-radii screw. Like the data at a barrel temperature of 75°C, the rate decrease was believed to be caused by the 11% lower cross-sectional area of the large-radii screw. As the pressure was increased to about 1.3 MPa, the rates for both screws decreased. But as the pressure was increased further, the rates continued to decrease for the small-radii screw but increased for the large-radii screw. At a discharge pressure of 5 MPa, the rate for the large-radii screw was higher than that for the small-radii screw.

For a barrel temperature of 125°C, the conveying rates at zero discharge pressure were 124 and 107 kg/h for the small and large-radii screws, respectively. As the discharge pressure was increased, the rates for both screws decreased in a very similar manner, as shown by Figure 4.

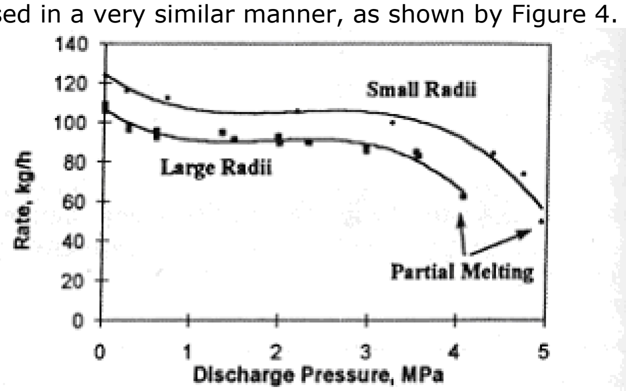

Figure 4. Solids conveying rates for a barrel temperature of 125°C, a screw temperature of 50°C, and 50 rpm

Figure 4

For discharges pressures less than 4 MPa, the large-radii screw had rates that were about 15% less than those for the small-radii screw. For both screws, the rates decreased as the discharge pressure was increased. Partial melting of some of the pellets were observed for both screws at this barrel temperature. For the small-radii screw, the onset of melting was observed at a discharge pressure of about 5 MPa. The onset of melting for the large-radii screw, however, occurred at a lower pressure of 4 MPa. The data suggests that a thermal effect is occurring at the barrel wall and that it is sensitive to pressure.

The solids conveying data indicate that two competing factors are controlling the rates. The rate reduction due to a decrease in the cross-sectional area perpendicular to the flight is the most obvious factor. As the radii of the flights are increased, the area perpendicular to the flight tip decreases and thus the volume available to convey material decreases. This factor is most apparent when the forwarding and retarding forces are minimal; i.e., at zero discharge pressure. At high discharge pressures, however, it is postulated that a channel with a large radius at the pushing flight will change the forwarding forces, as indicated by Figures 5 and 6.

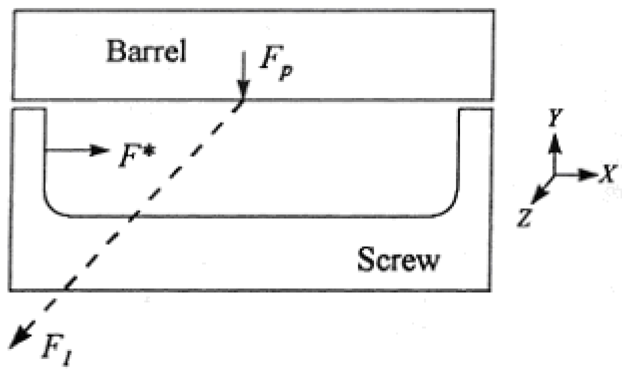

Figure 5. Schematic of the forwarding forces for a channel with small radii.

Figure 5

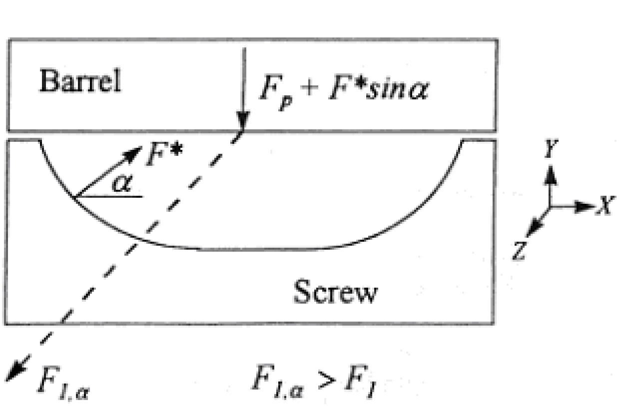

Figure 6. Schematic of the forwarding forces for a channel with large radii.

Figure 6

For a channel with a small pushing radius, the F* force (10) is directed through a surface that is parallel to the surface of the barrel, as shown by Figure 5. For this case the normal force at the barrel is due to the pressure in the channel, Fp; Fp produces the F1 forwarding force. For a channel with a large pushing radius, the F* force is partially directed towards the barrel like that shown by Figure 6. To counteract the component of the force directed at the barrel, the normal force at the barrel wall will increase by F*sina, causing the forwarding force F1 (labeled F1,a in Figure 6) to increase. The angle a is the angle between the acting force F* and a surface parallel with the barrel wall as shown by Figure 6. The higher forwarding force for the large-radii screw for high discharge pressures, F1,a, causes the rates to be higher than those for the small-radii screw. The larger normal force at the barrel wall for the large-radii screw causes larger amounts of energy to be dissipated at the interface, causing the onset of melting to occur at lower pressures. The F1 force is dependent on the coefficient of dynamic friction between the polymer and the barrel wall (10). This coefficient has been shown to be a function of temperature, pressure, and sliding velocity (6,12).

Although not investigated here, the effect of the radius on the trailing side of the channel is thought to only reduce the area available for conveying and not the forwarding or retarding forces. Thus, reducing the trailing flight radius will increase the area and improve solids conveying. Future research is planned that will explore this hypothesis.

In most cases, a screw designer does not have solids conveying or dynamic friction data for the resins to be processed. Thus, a detailed analysis of the forwarding forces as was done here will not be possible. The designer must con sider the consequences of flight strength, channel area perpendicular to the flight, and frictional forces when the flight radii are specified for an application. For example, if the coefficients decreased substantially with increasing pressure, the solids conveying rates may be reduced to levels considerably larger than that due just to an area reduction for a screw with large radii. Such a resin has not been investigated. For most design work, it is safer to maximize the area perpendicular to the flights in the feed section by minimizing the flight radii. Flight radii of about 1/4 the depth of the feed channel are likely safe for most resins.

METERING

Small radii in the metering section can produce regions where the residence times can be relatively long. For thermally sensitive resins, these long residence times can cause degradation of the resin, producing cross-linked gels or carbonized material. This degraded material will eventually break away from the screw and contaminate the extrudate. Figure 7 shows resin degradation at the pushing flight for a linear low density polyethylene (LLDPE) resin in the metering section of a 152.4 mm diameter screw.

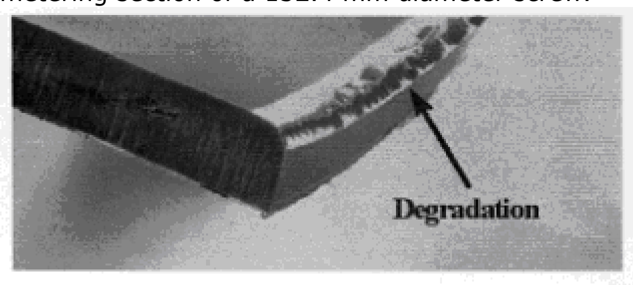

Figure 7

Figure 7. Degradation at the pushing flight radius for LLDPE and a 152.4 mm diameter extruder with an 18 mm deep channel and a 5 mm flight radius.

For this case the flight radii and channel depth were 18 and 5 mm, respectively, radii that are about 28% of the depth of the channel. Larger radii would have prevented the degradation by decreasing the residence time of material in the radii region.

The metering section of a 63.5 mm diameter screw channel with a depth of 3.18 mm was simulated using FIDAP (11), a commercially available computational fluid dynamics code, a three dimensional mesh, and a rate of 41 kg/h at 60 rpm. The procedures, method, and experimental verification were reported previously (4). For the simulations reported here, flow paths were calculated as a function of the flight radii size, both pushing and trailing, for the same LDPE resin used for the solids conveying experiments. The simulations were performed using a non-newtonian, isothermal rheological model and a rotating barrel reference frame.

Flow regions where the channel velocities were less than 10% of the maximum velocity are shown by the dark areas in Figure 8.

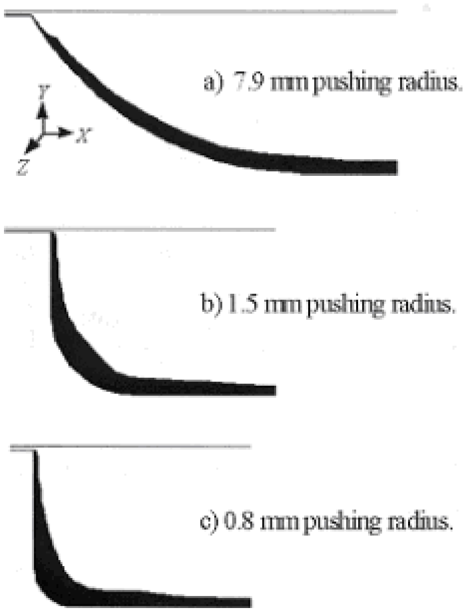

Figure 8. Simulated flows using FIDAP. Dark areas are regions where the velocities are less than 10% of the velocity at the barrel wall.

Figure 8

The figure shows these low flow regions at the pushing side of the channel. Low flow regions at the trailing side were similar to those at the pushing side. For Figure 8a, the flight radii were 7.9 mm and the regions of low flow were relatively low near the radius; the radius was about 2.5 times the depth of the channel. For Figure 8b, the radii were about half that of the depth of the channel, radii that would be specified if the SPI guideline were used. As indicated by this figure, the region for low flows and thus long residence times has increased in distance away from the screw radius; the thickness of the region is twice that of the 7.9 mm radii simulation. For radii of 0.8 mm, this region for low flows is even larger. Thermally sensitive resins may reside long enough in these regions to degrade and eventually contaminate the extrudate. In general, the choice of radii would depend on the thermal sensitivity of the resin, the type of degradation products, the rheological properties of the resin, and the quality of the extrudate required by the downstream equipment.

Some designers often decrease the radii for the metering section so that the cross-sectional area available for flow will be maximized for a given channel depth. These designers believe that the specific rate will be increased by decreasing the radii. The simulations were all made at 41 kg/h and 60 rpm. The pressure gradients for the three cases were essentially the same, indicating that the small radii did not change the rate.

For the metering sections of the screw, large radii are preferred for most resins so that long residence times regions near the radii are eliminated. Thus for most resins, the SPI guideline as a minimum is appropriate for this section, but larger radii are better; radii up to 2.5 times the depth are acceptable. For materials that do not adhere strongly to metal surfaces, the molten materials will tend to pull away from the walls of the screw, and thus even for very small radii there will be no regions with high residence times.

MELTING

Although not documented here, the flight radii in the melting section should be adjusted to reflect the amount of molten material present in the channel. Like the metering section, the goal is to minimize degradation of material at the flight radii. For example, at the entry region of' the melting section where only small amounts of molten material are present at the pushing side of the channel and the channel is relatively deep, the flight radii should be about that used for the solids conveying zone. When the melt pool becomes large such as at the exit of the melting section, the flight radii should approach the radii used in the metering section. Thus in order to minimize degradation, flight radii should slowly transition from the radii in the feed section to those in the metering section. This is the current practice used by most screw designers.

Conclusions

Solids conveying data indicated that the flight radii in the feed section results in two competing factors that affect rate:

1) reduced area for a channel with large radii, resulting in reduced rates, and 2) increased forwarding forces for a channel with large radii, leading to higher rates. Factor 1 dominates at low discharge pressures and factor 2 at high discharge pressures. The second factor is material dependent, and in most cases a small radii is recommended; radii of about 1/4 of the channel depth for the feed section is recommended. For metering and melting sections, the radii are selected in order to minimize degradation at the radii. For the metering section and most materials, the radii should be at least 1/2 to 3/4 the depth of the channel and up to about 2.5 times the depth of the channel. For the melting section, the flight radii should slowly transition from the radii in the feed section to those in the metering section.

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