

IMPROVED SCREW DESIGN FOR MAXIMUM CONDUCTIVE MELTING

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Abstract

New advances in screw designs and mixing sections have allowed processors to take advantage of new resins, higher production rates, and improved product quality. Until now, the basic single screw geometry has changed little over the past 15 years. With the advances in new material formulations, additives and fillers, the screw design must be able to fully melt and disperse the additives in the polymer matrix without destroying the properties from excess shear. This paper will present data on the melting performance of a new screw design with a unique flight geometry that maximizes the conductive melting mechanism (low shear) in the screw channel.

Background

Viscous energy dissipation via shearing in single screw extrusion has been the subject of intensive study over the last forty years. It is well documented in the literature that the polymer pellets start to melt after 2 to 4 diameters from the hopper and are compacted into what is known as a "solid bed", as shown by Figure 1. The initial melting mechanism of a tightly compacted solid bed is mainly by rubbing on the hot barrel surface as it rotates with the screw and by conductive heating from the barrel heaters (1). As the melt film between the solid bed and the barrel increases, heat is generated from viscous shear heating, which dominates the melting of the polymer. In conventional screws, viscous shear heating is the principle source of energy to melt the polymer. Previous work using solidification experiments (9) show the solid bed melting characteristics for a conventional screw, as shown by Figure 2. The white regions indicate material that was essentially solid while the gray colored regions indicate material that was molten and mixed with black tracer pellets. At 16 diameters, considerable amounts of unmelted resin existed in the channel, and at 19 diameters the break up of the solid bed has caused solids to be transported close to the tip of this 21 diameter long screw. These solids in the discharge will decrease the quality of the discharge and severely limit the performance of the screw, especially at high screw speeds and rates.

More modern screw designs utilize a barrier flight as shown in Figure 3. As the melt film is wiped off the barrel surface by the main flight, the melt is deposited into a separate melt channel. A barrier flight divides the solid and melt channels such that the clearance over the barrier flight will only allow melt to enter into this channel. The

main function of a barrier flight is to separate the melted polymer from the solid bed and keep the solid bed from becoming unstable and prematurely breaking up. By continuously removing the melt film over the barrier flight, the solid bed surface remains intact. This allows for a greater solid bed surface area on the barrel wall to keep the viscous energy dissipation via shearing as high as possible. In addition, since the melt film thickness over the barrier flight is small, the shear energy is also high. It is believed that this type of phase separation will increase the melting rates as compared to non-barrier type screws. However, since approximately 90% of the polymer is melted by the high shear in the barrier section, the melt temperatures are correspondingly higher, which is undesirable in many applications.

Recognizing the inherent problems and limitations of barrier type screws, the solid/melt mixing type screw was developed (1). This principle differs from the barrier designs in that the metering section is divided into two equal subchannels by a secondary flight. The solid bed is intentionally broken up at the end of the melting section to allow some solids to enter the mixing section. The clearance of the secondary flight is much greater than the clearance of the barrier flight on a barrier screw, allowing unmelted pellets to pass through. The depth of one subchannel decreases while the depth of the other increases, forcing the melt to flow over the secondary flight at relatively low shear rates, as shown by Figure 4. Solid bed fragments mixed in the melt are broken into individual pellets by passing over the secondary flight, as shown by the white colored regions of Figure 5 (9) at 16 diameters. The pellets are continually mixed with the melt promoting heat transfer by conduction from the melt to the pellets, as indicated by the solidification experiment shown by diameter 19 in Figure 5. This figure clearly shows that more of the resin was melted and mixed by 19 diameters as compared to the conventional screw (Figure 2), as indicated by the lower levels of white regions in the cross section. Since the viscous energy dissipation via shearing in solid/melt mixing screws is low and the primary melting mechanism is by conduction, the melt temperature is reduced.

There are two different solid/melt mixing screws commercially available, the Wave Screw (2, 3) and the Barr Energy Transfer (ET) screw (4-9). Both designs have been well researched and documented in the literature.

Based on our understanding and research on the melting mechanism in the ET design, as shown by Figure 6, it seemed possible to further increase the conductive melting capacity and achieve greater melting rates and improved extrudate qualities.

New Concept

The impetus of this work resulted from a blown film customer who was trying to blend a metallocene linear low density polyethylene (mLLDPE) resin with a fractional melt index (MI) low density polyethylene (LDPE) resin. There was considerable melt fracture in the film which was believed to be from residual metallocene resin solids or at least colder domains of the metallocene resin in the discharge. It was theorized that this was due to lubrication of the metallocene pellets by the lower viscosity LDPE resin. As a result, the metallocene domains could not be melted by shear due to the lubrication effect of the LDPE. Processing aids could be added to lessen the melt fracture, but this was an expensive route the customer did not wish to take.

As a result, we set out to design a new ET concept wherein a considerable length of the screw, around 50%, was used as an elongated ET section with many more channel peaks than in the older style ET, as shown in Figure 7. In addition to adding more peaks, the undercut clearance was gradually decreased until it reached a minimum value at the discharge end of the screw. To accomplish this meant eliminating the barrier section upstream of the ET section, which we had previously used for film applications. Since the shear levels in the ET section are relatively low compared to shear in a barrier section, most of the melting from the start of the ET section should be by conductive melting and since this new design has a solid/melt mixing section, at least twice as long as the older style ET, it should provide significantly more conductive melting. The objective of this variable barrier energy transfer (VBET, 10) design is to maximize conductive melting and minimize viscous energy dissipation via shearing. This screw design will be referred to as the New screw design in the rest of the paper.

Experimental

Tests were conducted on a 88.9mm diameter, 30 length-to-diameter (L/D) ratio blown film single screw extruder. The extruder was equipped with a single layer 280mm diameter die with internal bubble cooling (IBC) capability. Four different screw designs were tested: (A) standard barrier screw supplied by the extruder manufacturer, (B) an aftermarket barrier screw, (C) a non-barrier modified ET screw, and (D) a screw with the New design. The channel profile for the New screw design (D)

is graphically shown in Figure 8. All the screws were equipped with a Maddock type mixer on the discharge end of the screw with approximately the same mixer undercut clearance of. 0.51mm. The material used in the tests consisted of a blend of 45% 1.0 MI mLLDPE, 35% 1.0 MI LLDPE, and 20% 0.25 MI LDPE pellets. The combined density of the resin blend was 0.92g/cm³. A 2-mill average film thickness was maintained for each test. The objectives of this test were two fold. First, to evaluate the film quality at a required production rate of 181 kg/h. Second, to achieve maximum output rates before the onset of melt fracture without increasing the amount of processing aid; i.e., operate at higher rates without solids or cold metallocene domains in the discharge.

Results and Discussion

As indicated by the data in Table 1, the performance of the barrier screws was very similar. In addition, the barrier designs did not show any improvement in film quality and melt fracture reduction at the required output rate. The maximum output rates that the barrier screws ran without melt fracture were 91 and 94 kg/h for Screws A and B, respectively. The non-barrier ET screw showed a significant reduction in melt fracture at a rate of 181 kg/h. The New design, however, showed a remarkable improvement over the other screws and achieved a significantly higher output rate before the occurrence of melt fracture; i.e., a rate of 215 kg/h was achieved before the onset of melt fracture. By eliminating the barrier section in this design and intentionally breaking up the solid bed sooner, the viscous dissipation due to shearing was reduced. This suggests that the primary melting mechanism for the New screw design is by conduction from the hot melt to the cool solids and not by viscous energy dissipation via shearing. The data indicates that the specific rate increased by 15% compared to the non-barrier ET design and 17% compared to the barrier designs. Moreover, the New screw design produced a discharge at high screw speeds with a melt temperature that was 9°C less than the barrier screws tested.

The extruder used in this test did not have the capability of measuring the melt temperature distribution across the melt stream. However, subsequent trials have been made on other blown film lines, as shown by Table 2, utilizing the New screw design. One case in particular, the extruder was equipped with a variable depth thermocouple (VDT). The operating conditions are listed in Table 3. The melt temperature was measured in the adapter tube at the discharge end of the screw upstream of the screen changer. Measurements were taken every 3.2mm across the melt stream starting at 9.5mm from the adapter wall. As indicated in Figure 9, the total melt temperature gradient across the melt stream at screw

speeds of 26 to 35 rpm was 5 to 3°C, respectively. This temperature gradient is relatively small and highly acceptable for commercial applications.

Conclusions

This work was originally implemented to solve a specific processing issue. The results of our tests suggest that a design that maximizes conductive melting as the primary melting mechanism can improve the melt quality at high rates. Data from a subsequent test indicated that a more uniform melt temperature distribution can be obtained for the New design as compared to barrier type screws.

Future studies are planned to fully examine the complex melting and mixing mechanism of this new design in order to optimize its performance.

References

1. C.I Chung, *Extrusion of Polymer*, Hanser, (2000).
2. G.A. Kruder and W.N Calland, *SPE ANTEC Tech. Papers*, **36**, 74 (1990).
3. G.A. Kruder, U.S. Patent 4,173,417, HPM Corp.
4. "ET" Registered Trademark of Robert BARR Inc.
5. C.I. Chung and R.A. Barr, *SPE ANTEC Tech. Papers*, **29**, 168 (1983).
6. C.I. Chung and R.A. Barr, U.S. Patent 4,405,239.
7. T.A. Plumley, M.A. Spalding, J. Dooley, and K.S. Hyun, *SPE ANTEC Tech. Papers*, **40**, 324 (1994).
8. S.A. Somers, M.A. Spalding, J. Dooley, and K.S. Hyun, *SPE ANTEC Tech. Papers*, **41**, 222, (1995).
9. B.A. Salamon, M.A. Spalding, J.R. Powers, M. Serrano, W.C. Sumner, S.A. Somers, and R.B. Peters, *Plast. Eng.*, **57**, 4, 52 (2001).
10. R.A. Barr, U.S. Patent Pending (2001).

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Key Words:

Solid Melt/Mix, Conductive Melting, ET.

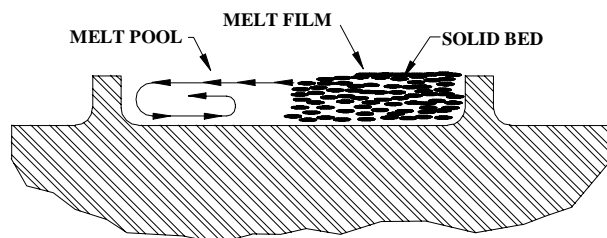


Figure 1. Conventional Screw Channel Flow

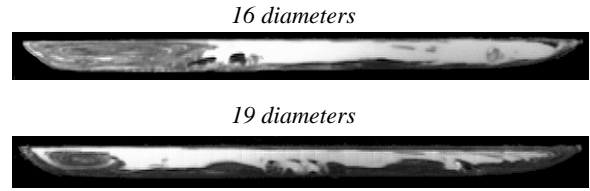


Figure 2: Channel cross sections for the conventional extruder screw (9).

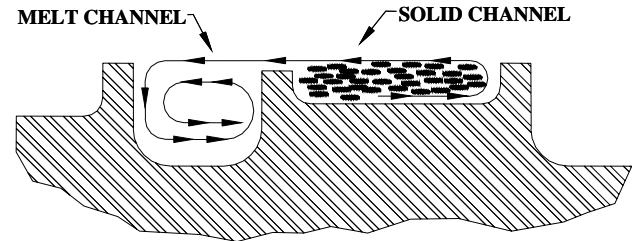


Figure 3. Barrier screw channel flow.

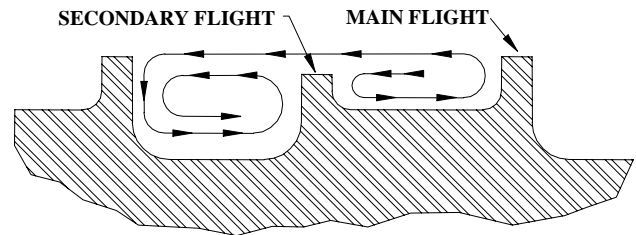


Figure 4. Solid/melt mixing channel Flow.

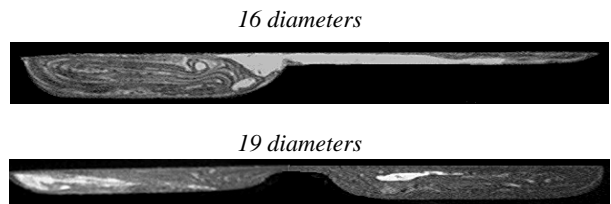


Figure 5: Channel cross sections for the ET extruder screw (9). The white regions are un-melted resin while the gray regions indicate molten and well mixed resin.

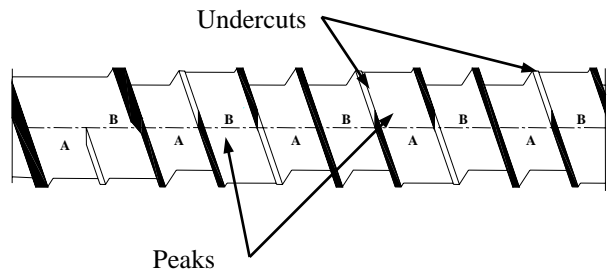


Figure 6. Schematic of an ET section.

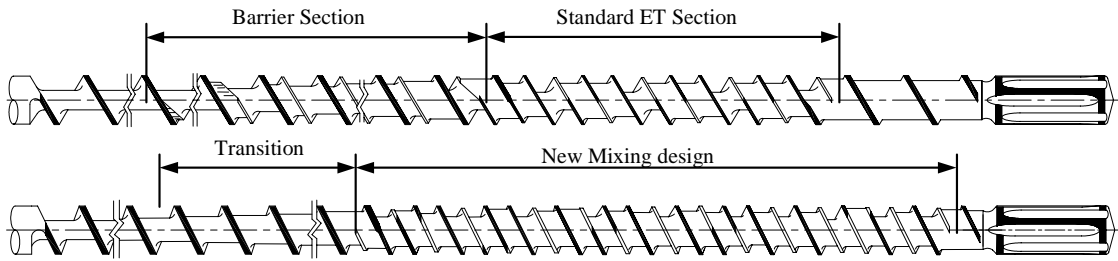


Figure 7. Standard barrier ET vs. New design.

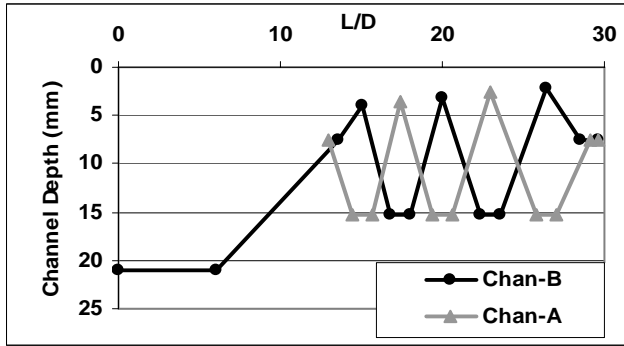


Figure 8. Channel depth profile for the 88.9mm diameter, 30 L/D New Screw design.

Screw Type	Barrier A	Barrier B	ET C	New Design D
Rate, kg/h	91	95	127	215
Screw Speed, rpm	30	31	41	59
Specific Rate, kg/(h rpm)	3.0	3.1	3.1	3.6
Melt Temp °C	254	253	258	245
Discharge Pressure, MPa	16.6	18.3	20.7	31.2
Specific energy,* J/g	491	474	522	558

Table 1. Maximum performance before the onset of melt fracture.

*Specific energy inputted by the screw.

Screw Diameter (mm)	130
L/D	28:1
Material	1.0 MI LLDPE
Solid Density (g/cm ³)	0.919

Table 2. Blown film extruder used to measure melt temperature variation.

Rate, kg/h	273	323
Screw speed, rpm	26	35
Specific Rate, kg/(h rpm)	10.5	9.2
Discharge Pressure, MPa	20.8	23.4
Specific energy,* J/g	567	745
Melt Temp °C	227	232
Delta T °C	5	3

Table 3. Performance for the 130mm diameter New Screw.

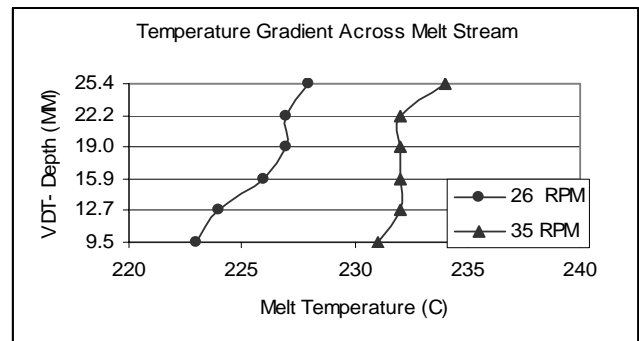


Figure 9. Melt Temperature gradient across the melt stream for the New Screw.