ADVANCEMENTS IN SCREW DESIGN TECHNOLOGY FOR THE BLOWN FLIM INDUSTRY

Jeff A. Myers- BARR Inc., Onsted, MI

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. 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 review the melting performance of typical blown film screw designs currently available and 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, Figure 4. 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 5. 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 6. 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 7, 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 reduce 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 8. In addition to adding more peeks, 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 Case-1

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. 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/cm^3. 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, and 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

As indicated by the data in Table 1, the performance of the barrier screws were 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^{o}C less than the barrier screws tested. The extruder used in this test was a production machine and was not equipped to fully evaluate all the performance parameters of the new design.

Experimental Case-2

Subsequent experiments were performed on a highly instrumented 88.9mm diameter extruder with a 30 length-to-diameter ratio. The extruder was equipped with a single layer 203mm diameter die with internal bubble cooling (IBC). The die gap was set at 2.54mm and had a 2.5:1 blow up ratio. This extruder was equipped with five pressure transducers located along the axis of the barrel to measure pressure along the screw and five-barrel temperature control zones. The melt temperature was measured using a variable depth thermocouple (VDT) located in the adapter pipe downstream from the screen changer. The material used in this study was a DOWLEX (11) 1.0 MI LLDPE 100% virgin pellet with a .92 g/cm^3 density. The three screws that were used in this study consisted of a standard barrier ET screw with a Maddock type mixing head, New VBET design with a Maddock type mixing head, and a New VBET design without a mixing head. The channel profiles are summarized in Table 2. The setup parameters were held constant for each screw during the test and are shown in Figure 9.

The melting performance for each design was evaluated based on discharge temperature (^{o} C), energy usage (J/g), and extrusion rate (kg/h) at 20, 40, 60, and 89 rpm. A gel counter device was used to evaluate the presence of unmelt and gels in the film and recorded at 20 and 40 rpm.

Results

As indicated in Figure 10, the extrusion rate (kg/h) for the New design with and without the Maddock mixing head showed a significant improvement over the barrier ET design. These results are consistent with what we would expect by eliminating the restriction of the barrier section. The screw power consumption (kw) was recorded at each rpm and is shown in Figure 11. The specific screw energy required (J/g) as shown in Figure 12 was lower for the New design, which suggests that the energy from the screw is better utilized and more efficient than the barrier ET design. This also suggests that additional melting by conduction was the primary melting mechanism. The pressure profile along the axis of the screw was recorded and is consistent with normal operation. Figure 13 shows a typical pressure profile at 40 rpm.

The melt temperature uniformity across the melt stream was measured using a variable depth thermocouple (VDT) located in the adapter. Measurements were taken every 1.5mm across the melt stream starting at 4.7mm from the adapter wall. The results for 40 and 89 rpm are shown in Figure 14 and Figure 15 respectively. This temperature gradient is relatively small and highly acceptable for commercial applications.

A gel counter device was used to evaluate the quality of the films as it exited the die. The results are summarized in Table 4. The results for all three screws tested were well below an acceptable range. It is interesting to note that the New design without the Maddock mixing head had the lowest gel rating values compared to the barrier screw with a Maddock and the New design with a Maddock. This suggests that the longer solid/melt section in the new design was capable of fully melting the material at lower shear rates.

Conclusions

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 indicated that eliminating the barrier section and increasing the Solid/Melt mixing section can increase the extrusion rates without sacrificing the quality of the discharge. The discharge temperatures were lower for the New design with and without the Maddock mixing head compared to barrier ET screw, with improved melt temperature distribution. The specific screw energy (J/g) required was lower for the New design at increased rates which indicate reduced viscous shear heating. The film quality with the New design exceeded the material suppliers specification as indicated by the gel count analysis. This also suggests that the New design without the Maddock mixing head will not have a negative effect on the film quality.

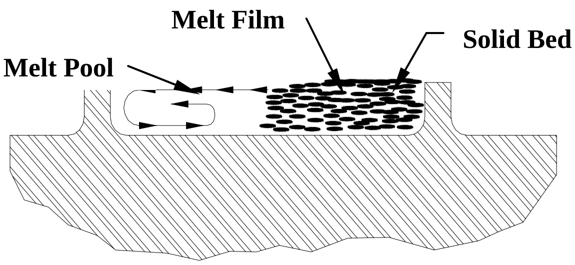

Figure 1. Conventional Screw Channel Flow

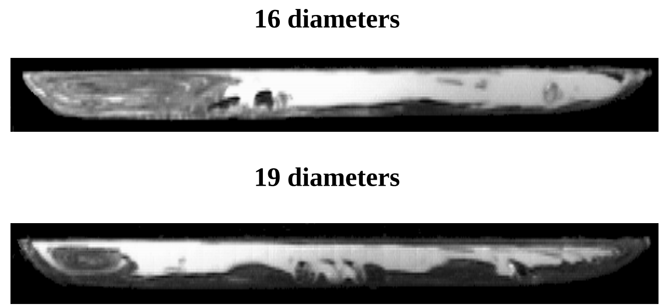

Figure 2. Channel cross sections for the conventional extruder screw (9).

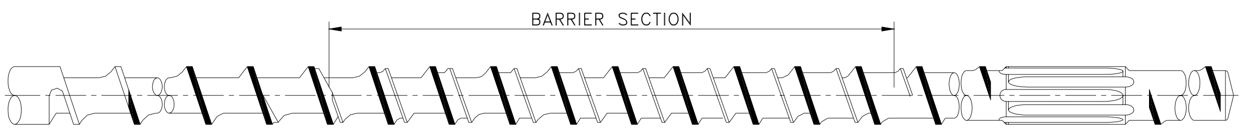

Figure 3. Typical Barrier screw

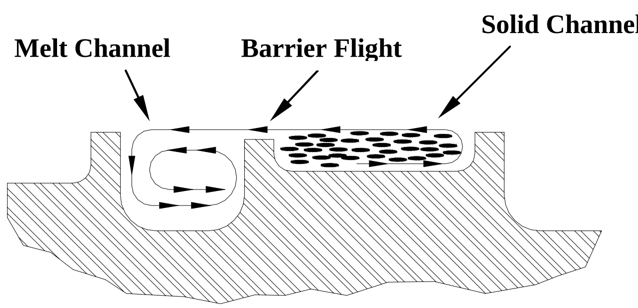

Figure 4. Barrier screw channel flow

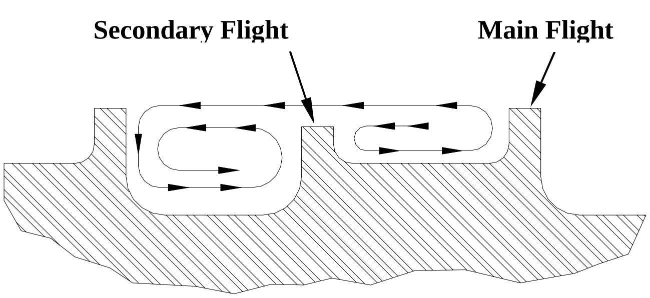

Figure 5. Solid/melt mixing channel Flow

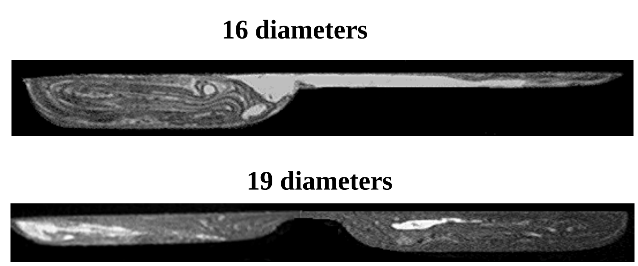

Figure 6. Channel cross sections for the ET extruder screw (9). The white regions are un-melted resin while the gray regions indicate molten and well-mixed resin.

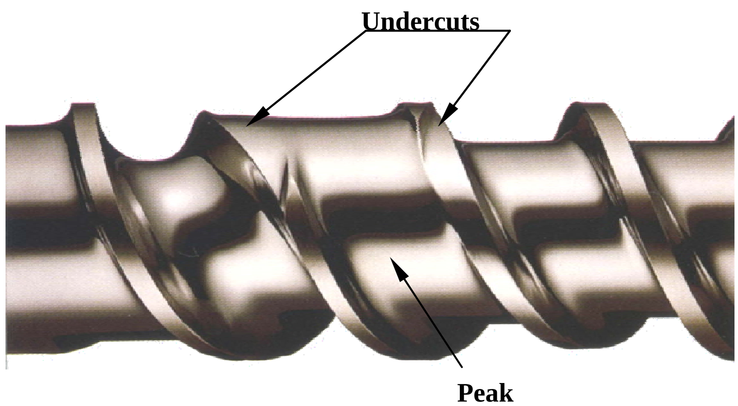

Figure 7. ET section.

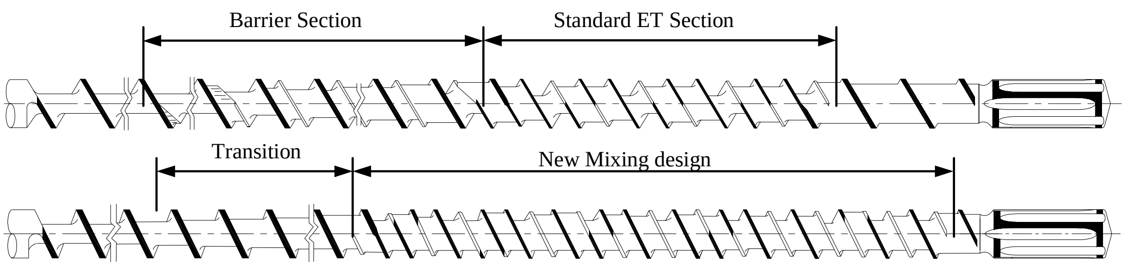

Figure 8. Standard barrier ET vs. New design.

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 ^{o}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 performances before the onset of melt fracture.
*Specific energy inputted by the screw.

Screw Type	Barrier ET w/Maddock	New VBET w/Maddock	New VBET w/out Maddock
Feed Depth (mm)	20.7	20.7	20.7
Feed Length (L/D)	6.5	5	5
Barrier Length (L/D)	7	N/A	N/A
Meter Depth (mm)	8.3	8.3	8.3
Meter Length (L/D)	3.5	1	5
Peak Clearance (mm)	3.2	3.5 to 1.5	3.5 to 1.5
Lead (mm)	108	108	108
Maddock Clearance (mm)	.76	.76	N/A

Table 2. Channel profile for the 88.9mm diameter, 30 L/D Screws.

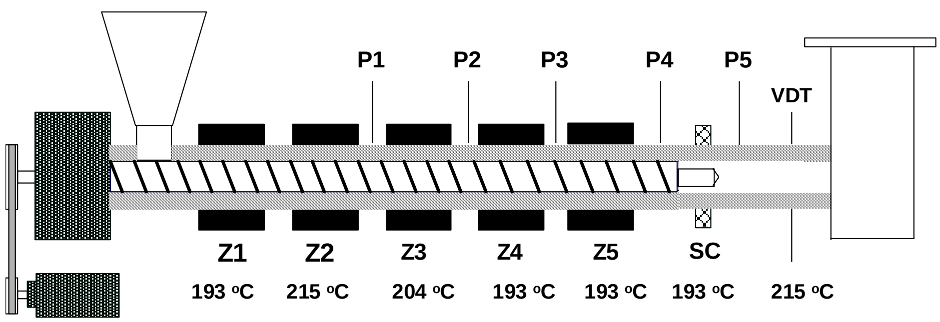

Figure 9. Setup conditions for the 88.9mm diameter, 30 L/D Screws

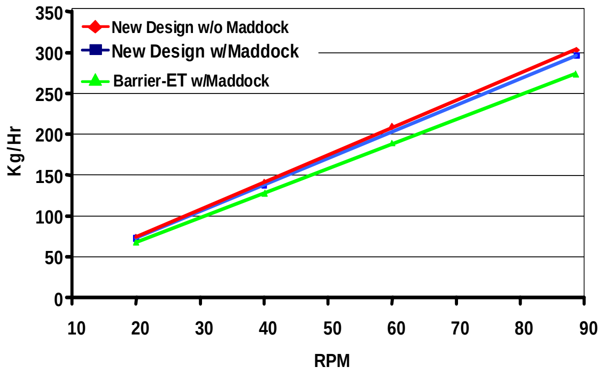

Figure10. Extrusion Rate (kg/h) Vs. rpm

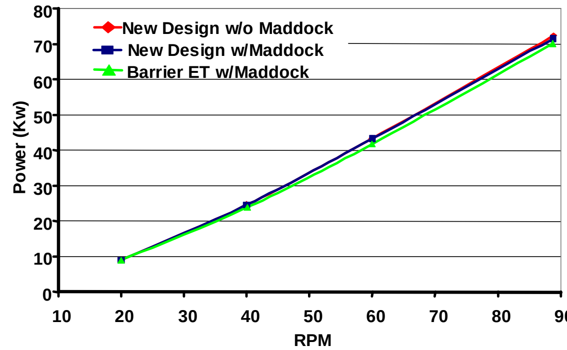

Figure 11. Screw Power Consumption (kw) Vs. rpm

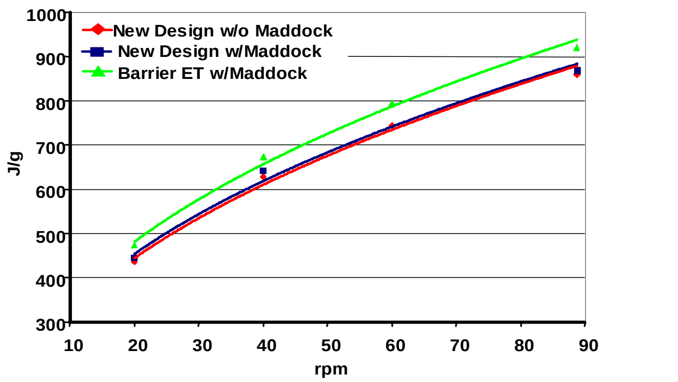

Figure 12. Specific Screw Energy Required (J/g) Vs. rpm

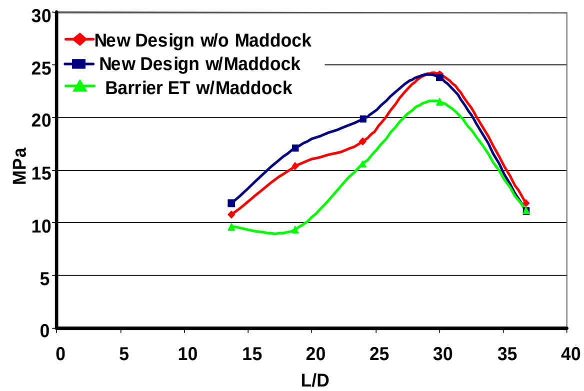

Figure 13. Pressure Profile at 40 rpm

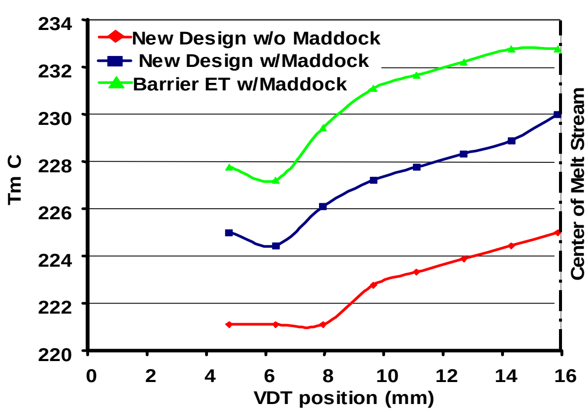

Figure 13. Melt Temperature Gradient at 40 rpm

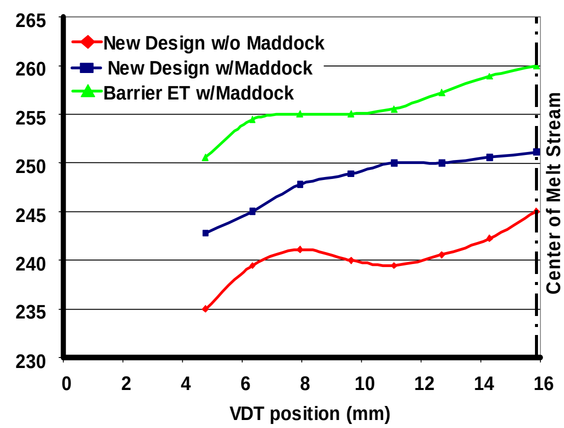

Figure 14. Melt Temperature Gradient at 89 rpm

Screw Type	Barrier ET w/Maddock	New VBET w/Maddock	New VBET w/out Maddock
Average (Avg + 2xStd Dev)	0.53	0.47	0.20
Standard Deviation	0.60	0.47	0.27
Gel Rating (mm^2 / 26.4 cm^2)	1.72	1.42	0.74

Table 4. Gel count Analysis at 89 rpm

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Key Words:

Solid Melt/Mix, Conductive Melting, ET.