NEW CONCEPT FOR MELTING IN SINGLE-SCREW EXTRUDERS

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Abstract

In the late 1950's Union Carbide's research engineer, Bruce Maddock, ran several single-screw extruder experiments. He established a method to reveal the melting profile in the screw by stopping the screw and quickly cooling it to freeze the polymer [1]. Then he reheated it to create a melt film on the barrel surface so he could pull the screw out. The condition of the polymer in the screw flights was studied. This revealed what Maddock called the solid bed melting mechanism. He showed that at the end of the feed section there was a tightly packed mass of solids in the screw channel. Melting occurred at the barrel surface as the conventional transition section decreased in depth. The melt was scrapped off the screw barrel surface by the rotating screw flight which deposited it into the rear of the screw channel. Thus, the solid bed melting mechanism was discovered. This mechanism has been the basis of all screw designs since. This paper will disclose an alternate melting mechanism which does not use the solid bed theory.

Background

Since the late 1950's, due to work done by Bruce Maddock of Union Carbide, the solid bed theory of melting has dominated extruder screw design [1]. All subsequent improvements in screw design have been based on this theory. Although the theory is fact, as proven by numerous experiments and by the melting equations developed by Tadmore and Klein in the 1960's [2], it may not be the only way of melting plastic in an extruder screw. The natural behavior of the unmelted plastic entering the extruder screw from the feed hopper and being conveyed forward by the helical flights is formed, by channel depth reduction, into a solid mass or solid bed of unmelted plastic, no matter the feed form, (pellet, powder, or regrind). This solid mass is referred to as the solid bed. As this bed is forwarded down the screw channel transition section, the channel depth reduction causes the solid bed to be forced into pressurized contact with the extruder barrel forcing melting to occur at the barrel-solid bed interface due to the shear stress in the melt film. By the forwarding action of the helical flights the melt is then scrapped off the barrel surface by the trailing screw flight forcing it into a developing melt pool at the rear of the solid bed, as shown by the photograph in Figure 1 [3] and the schematic in Figure 2. Since the solid bed itself is a tightly compacted mass, no mixing of the plastic can occur. In addition, at the end of the channel depth taper of the transition section, the remaining solid bed can exert very high pressure in the channel. This pressure can create high wear on the screw diameter flight. This phenomenon is known as "solids wedging." Further downstream, the channel depth remains constant thus no further compression can occur, so the solid bed will break up into solid particles now floating in the melt stream. Most screw design developments to date have been aimed at completing the melting and mixing of the remaining solids to ensure a uniform melt exiting the extruder. Some designers, such as Maillefer and Barr, have controlled the solid bed by using a barrier flight in the screw channel. This flight can be at a different lead than the main flight, and thus forcing the solid bed to be reduced in width as it moves down the screw channel; i.e., the Maillefer design [4,5]. Or by using a same lead of the barrier flight between the solids and melt channels but reducing the solids channel depth to force the solid bed onto the barrel surface and increasing the melt channel depth to accommodate the increasing melt volume; i.e., the Barr design [6]. Multiple variations of these concepts have been created over the last almost 60 years, but all still rely on the solid bed theory of melting [3].

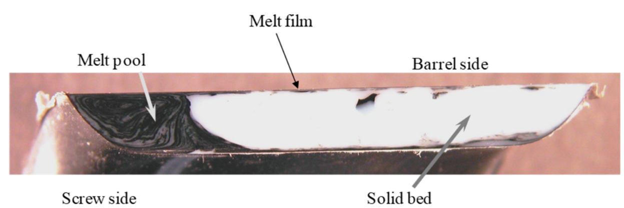

Figure 1. Photograph of resin solidified in the transition section after a Maddock solidification experiment for an ABS resin [3]. The pushing flight is on the left side of the photograph. The white material (with a black masterbatch) was solid when the screw was stopped, and the black material was molten.

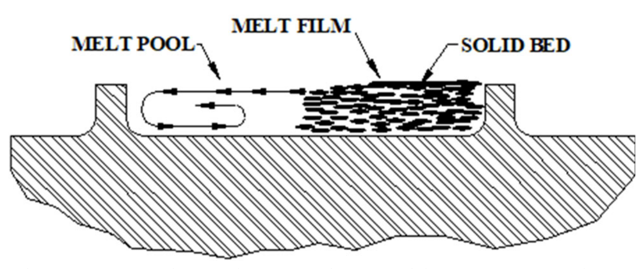

Figure 2. Schematic of the melting process in a conventional screw transition section.

Barr's later patent called the ET (Energy Transfer) screw [7,8] provided improved melting of the remaining solid bed, at the end of the tapered or transition section of the screw, by shuffling the melt/solid mix back and forth between adjacent channels over a barrier flight to improve conductive melting of the remaining solids. The performance and numerical simulation were presented by previously [9,10]. This design has proven successful as has its successor, the VBET screw [11], ensuring that no stationary melt film can exist around the remaining solid particles, thus improving the heat transfer from melt to solid. A schematic of a VBET screw section is shown by Figure 3. A performance analysis for the VBET was performed by Hogan et al. [12], including a Maddock solidification experiment.

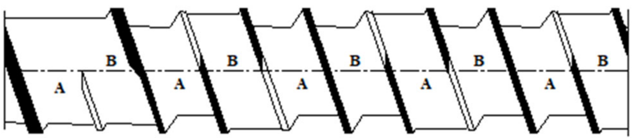

Figure 3. Schematic of a VBET screw section.

Note that the solid bed mass, in solid bed melting, is only exposed to heat input from its four sides. (i.e.- barrel surface, melt pool, screw root surface and forward flight surface). In the "No Solid Bed" (NSB) design presented here the thought is to be sure that each of the solids, pellet or powder particles, is surrounded by molten polymer. This ensures that there is a maximum heat transfer into the relatively small solid particle. If this melting is started as soon as there is a melt film on the barrel, then the solid bed cannot be formed. This is the principle concept behind the NSB screw design described next.

New Concept

The concept of this invention is to use varying channel depths in the transition section to keep the solid particles moving back and forth in the main channel. This is accomplished by having two, or more, channel depth profiles between the flights of the screw, as seen in Figure 4. The total volume of the screw channel is gradually reduced from the inlet of the screw transition section to the end of melting determined by the chosen compression ratio. But, with each, approximately, one turn of the screw from the inlet the forward portion of the channel's depth is reduced while the rear portion is increased. This forces the feed material to be shuffled from the front to the back of the channel and then in approximately the next lead the action is reversed forcing the particles to move into the forward portion of the channel. This shuffling action prevents a solid bed from forming but also allows the melt from the barrel surface to be mixed into the solid particles, promoting melting. There is no barrier flight in the melting section which might prevent free movement of the solid pellets from the forward channel portion to the rear and vice versa. The proposed design is shown in Figure 4.

Experimental

Tests were conducted on a 63.5 mm diameter, 33 length-to-diameter (L/D), single-stage single-screw extruder with four temperature control zones. The machine was equipped with a simple rod die with a 12.7 mm diameter discharge opening. The die was equipped with a restrictor valve to adjust the discharge pressure. The barrel was instrumented with three pressure transducers with the locations at 895, 511, and 2,027 mm from the feed pocket for P3, P2, and P1, respectfully. The tests were done at barrel temperatures of 185, 210, 220, and 220°C, for zones 1 through 4 respectively. All downstream sections were maintained at 220ºC. Two different screw designs were tested and consisted of: (A): Standard VBET solid/melt design Figures 3, and (B): VBET-NSB with a modified feed and transition section, as shown in Figure 4. The channels profiles are graphically shown in Figures 5 and 6, respectfully. Both screws had the same depth profile geometry in the feed, meter, and VBET sections. Schematics of the screws are provided by Figure 7.

The material used in the tests low density polyethylene (LDPE) 501i resin. The resin had a melt index (MI) of 1.9 dg/min (190ºC, 2.16 kg) and a solid density of 0.921 g/cm^3. The resin was manufactured by Dow, Inc.

These early stage experiments are focused on the overall performance of the VBET-NSB screw versus a standard VBET screw as a function of screw speed and discharge pressure. The objectives of this test were to evaluate the extrudate quality, output rate and pressure tracings for each screw.

Results and Discussion

As indicated by the data in Figures 8 through 12, the performance of (A, B) screws are very similar. In addition, the (B) design did not show any adverse effect in stability, melt quality, or air entrapment. The only significant difference in the performance of the two screws was the value of the maximum pressures shown at P3. The VBET-NSB screw had about half the pressure recorded for the VBET screw at the same melting rates. This data suggests that the mechanism to break up the solid occurred over the length of the transition section and was fully melted at the end of this section. This also implies that the melting rate of the new design may be significantly higher than originally estimated.

The discharge temperature for the two screws are shown in Figure 10. The VBET-NSB screw had a slightly higher discharge temperature. The rates, specific rates, and power consumption were essentially identical for the two screws, as shown by Figures 8, 9, and 11.

The results of the VBET-NSB at 40 rpm are shown in Table 1 at different P1 discharge pressures. The data is consistent with expected results at higher discharge pressures. That is, the rate and specific rate decrease with increasing discharge pressure, and discharge temperature and power increases.

Table 1. Performance of the VBET-NSB at 40 rpm as a function of discharge pressure (P1).

Rate Kg/hr	Specific Rate Kg/hr/rpm	Power kW	Melt Tm,°C	P3 Mpa	P1 Mpa
46.31	1.158	15.84	228.3	3.0	4.0
43.31	1.083	16.68	230.0	3.9	6.6

The extruder used in this test did not have the capability of measuring the melt temperature distribution across the melt stream. However, subsequent trials are planned to incorporate this in the data.

Conclusions

At the time preparing this paper it was difficult to make firm conclusions as to the improved performance of the new VBET-NSB design. One benefit seems to be that the troublesome screw wear problems like solid bed wedging that plague the industry can be avoided with the VBET-NSB concept. The author feels that it is very possible that the NSB melting model may also result in much higher melting rates per turn of transition than with the solid bed model. The results of our test suggest that a design that breaks up the solid bed sooner in combination with a solid/melt design can improve the life of the screw without sacrificing the melt quality and specific rate. In addition, it seems possible that melting may be completed before reaching the end of the transition section implying a higher melting rate per turn than with the solid bed model. Future work using the Maddock freeze method may illuminate this possibility.

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

Acknowledgements

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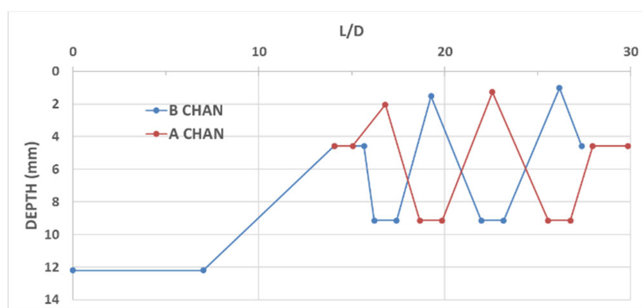

Figure 5. 63.5 mm, 33 L/D VBET channel profile.

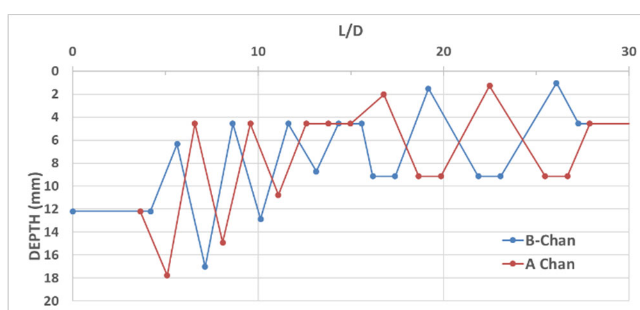

Figure 6. 63.5 mm, 33 L/D VBET-NSB channel profile.

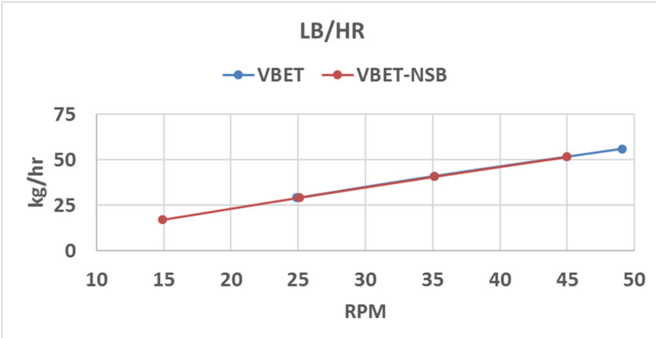

Figure 8. Rate as a function of screw speed.

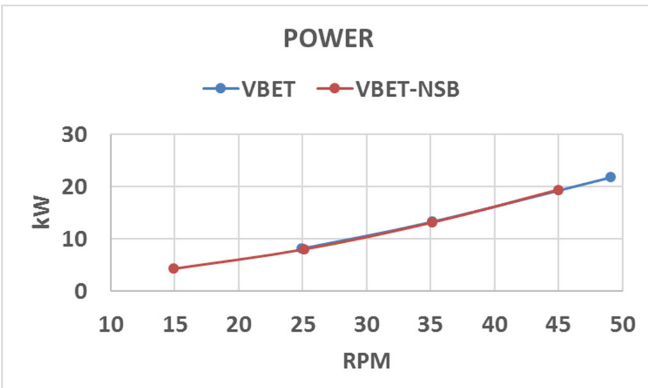

Figure 9. Power required as a function of screw speed.

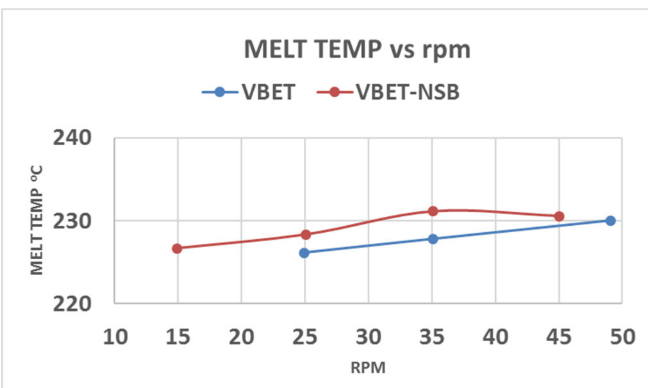

Figure 10. Discharge temperature as a function of screw speed.

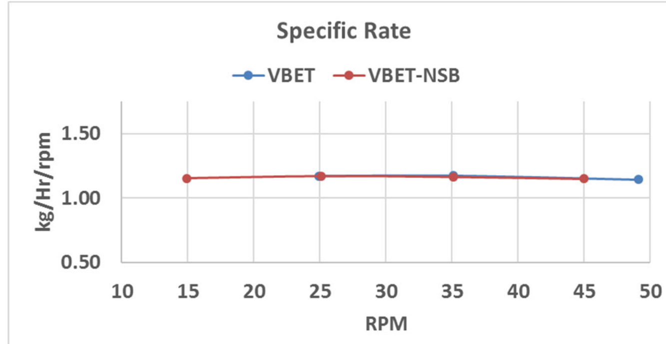

Figure 11. Specific rate as a function of screw speed.

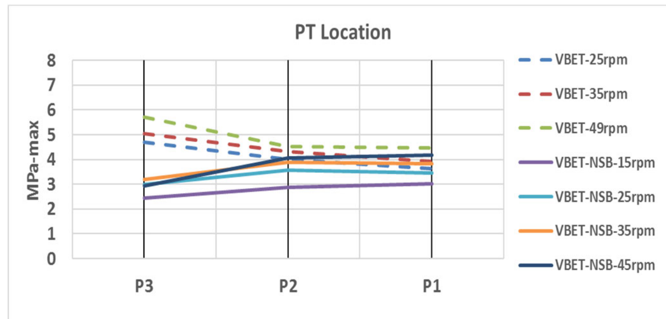

Figure 12. Axial pressure profiles as a function of screw speed.

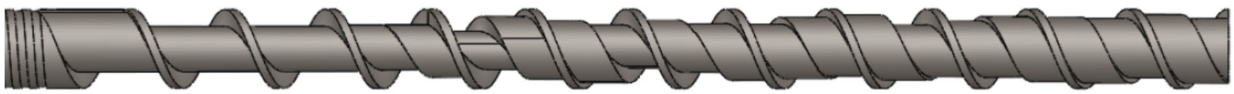

Figure 4. Schematic of VBET-NSB. Section

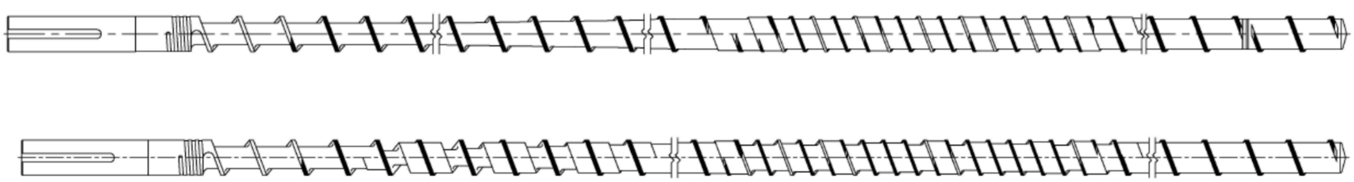

Figure 7. Schematic of VBET and VBET-NSB.