EXPERIMENTAL STUDY ON THE ENERGY EFFICIENCY OF DIFFERENT SCREW DESIGNS FOR INJECTION MOLDING

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Abstract

New advances in screw designs and mixing sections have allowed processors to advantage of new resins, higher production rates, and improved product quality. With new material formulations, and increased energy cost it is paramount that the machine utilize the total energy input in the most efficient manner. This paper will present data on the melting performance of a new injection screw design with a unique flight geometry that maximizes the conductive melting mechanism (low shear) in the screw channel. A comparison is made between the total energy required for melting, pumping and mixing characteristics between a standard General purpose screw, barrier screw and a new Variable Barrier Energy Transfer screw (VBET) (12).

Background

Injection molding is the most widely used plastic forming process in the industry today. The cost of each part produced depends on a number of factors including resin, cycle time, total energy input and scrap rate just to name a few. In general, the lowest cost per part will occur at the highest production rate and the lowest energy usage. The majority of the energy required to fully melt the resin is dictated by the screw design selected.

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 (2).

More modern screw designs utilize a barrier flight as shown in Figure 2. 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 channel 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. The pellets are continually mixed with the melt promoting heat transfer by conduction from the melt to the pellets. 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 (3).

The goal of this work is to evaluate the total energy requirements for the molding machine with three different screw designs and make a comparison on the performance and energy each screw required at different molding conditions.

Material

The resin used for this study was a standard injection grade High Density Polyethylene (HDPE), Fortiflex T50-500 grade. The melt flow rate (MFR) of the resin was 6.5 g/10 min (190 ^{0}C, 2.16 Kg). All tests were performed using 100% virgin natural pellets.

Equipment

The experiments were performed on a Milacron MM-550 (4) injection machine with the specifications listed in Table 1. The barrel was fitted with standard Ceramic heater bands. The total kW per zone is listed in Table 2.

The General purpose (GP) and Barrier screw that were evaluated are typical designs supplied by the machine manufacture.

The GP screw had a 100mm constant lead-length and a primary flight clearance of 0.10mm. It had a 12-diameter feed section that was 12.70mm deep, a 5-diameter constant taper transition section, and a 5-diameter constant depth meter section that was 4.70mm deep.

The Barrier screw had a 9.4-diameter feed section that was 14.50mm deep with a 100mm lead-length, 8.0 diameter barrier section with a 125mm lead-length, and a 2.6 diameter constant depth meter section that was 5.33mm deep. The feed and metering section were single flighted and the barrier section was designed with a melt and solid channel as shown in Figure 2. The clearance over the barrier flight had a constant depth of .51mm. The barrier screw had a 2.0 diameter spiral mixing section at the discharge end.

The VBET solid/melt mixing design had a lead-length of 120.7mm and a primary flight clearance of 0.10mm. It had a 6.0 diameter feed section that was 19.0mm deep. The constant taper transition section was 6.4 diameters long with a starting depth of 19.0mm and ending at 7.6mm depth. The solid/melt mixing section was 6.9 diameters long with a starting depth of 7.6mm and exit depth of 6.9mm. Within the mixing section the channel depth varied between 3.8mm and 12.7mm. As shown in Figure 4, the depth and length of the undercut flight varied through the length of the mixing section. The starting depth of the first peak was 3.8mm and the ending depth was 2.5mm. The period of these oscillations was out of phase for the two channels. The constant depth meter section was 1.3 diameters long at 6.9mm deep. The discharge end of the screw had a 1.0 diameter slotted mixing section. This screw design will be referred to as the Mixing screw in the rest of the paper.

Experimental

The barrel heater zones and screw motor were connected to a data acquisition systems which allowed the total power to be recorded for each test. A meter was installed on the main power supply which recorded the total machine power required for the duration of each test. To investigate the total energy input for each screw, the molding parameters were held constant throughout the test and are listed in Table 3. Data was recorded for fifty consecutive shots once the machine was at steady state.

Results and Discussion

The screw Recovery Rate (g/sec) is shown in Figure 5. The Mixing screw had an 18% higher rate compared to the GP design and a 15% higher rate compared to the Barrier design at 150 rpm. The melt temperature was measured using a hand held pyrometer after the last consecutive shot in each test. The maximum discharge temperature at 75 and 150 rpm is shown in Figure 6. The discharge temperatures for the Mixing Screw were 14 to 12 ^{o}C lower than the Barrier design at 75 and 150 rpm respectively. The melt quality for the Barrier and Mixing screw showed no sings of unmelt. The melt quality of the GP design showed evidence of unmelts at 75 and 150 rpm. At 150 rpm, unmelted pellets were more evident in the purging and the molded part. This data is consistent with the low discharge temperature with the GP design.

The specific energy inputted by the screw is shown in Figure 8. The Mixing screw used 6 to 12 % less energy compared to the GP and Barrier design. The varying depths in the solid/melt section of the Mixing screw allowed energy from the screw to be used more effectively. Shear energy inputted to the melted resin in the shallow channel regions was readily transferred to the cooler solids in the deep channel by conduction.

The total energy required, E_t to produce a single part is calculated from the following relationship:

$$E_t = P_t / R_M \,; \text{ kW/kg} \qquad (1)$$

$$R_M = 3.66 * W_t / C_T \,; \text{ kg/hr} \qquad (2)$$

Where P_t is the total machine power in kW. R_M is the machine specific rate in kg/hr, which is a function of the cycle time. W_t is the part weight in grams, and C_T is the total cycle time in seconds. The results at 75 and 150 rpm are listed in Figure 9. The Mixing screw required 1.6 to 2.6% less energy per molded part compared to the Barrier and GP design. The actual value would be higher if scrap rates and are included in the calculation.

Conclusions

Machine efficiency is an important aspect in the molding process. The data clearly shows that screw design plays an important role in the total energy required to produce a molded part. The results of our tests suggest that a design that maximizes conductive melting as the primary melting mechanism requires less energy per part than a GP or Barrier design. Data from a subsequent test indicated that the Mixing screw is able to produce a more uniform melt temperature distribution and improved mixing which can also improve the overall machine efficiency.

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Key Words:

Solid Melt/Mix, Conductive Melting, VBET.

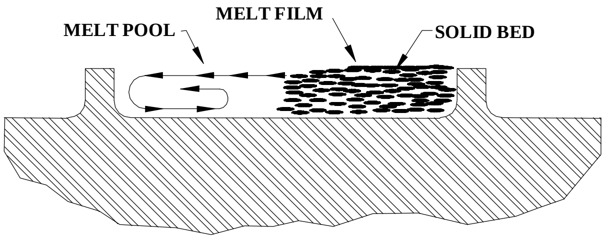

Figure 1. Conventional Screw Channel Flow

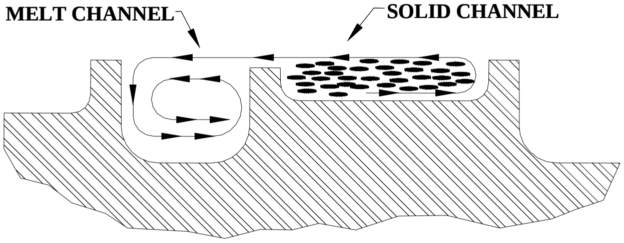

Figure 2. Barrier screw channel flow.

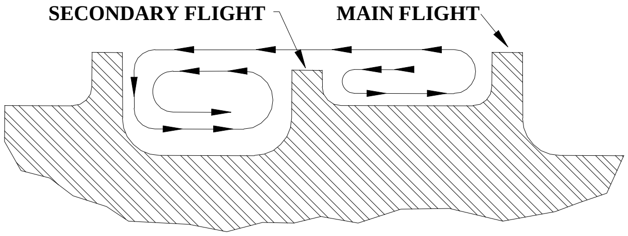

Figure 3. Solid/melt mixing channel Flow.

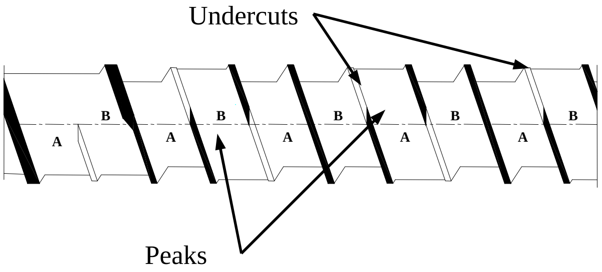

Figure 4. Schematic of VBET section.

Injection Capacity, Max G.P. Styrene , kg	2.98
Screw Diameter, mm	100
L/D	22:1
Maximum Screw Stroke, mm	400
Electric Screw Motor, kW	75
Maximum Screw, rpm	200
Number of Heater Zones	5
Total Heating Capacity, kW	53.8

Table 1. Machine Specifications.

Zone	kW per zone
Zone -1-Feed end	11.5
Zone-2	11.5
Zone-3	11.5
Zone-4	19.0
Total	53.50

Table 2. Heater Zone Specifications

Screw Speed, rpm	75, 150
Back Pressure, Bar	6.2
Feed Throat, ^{o}C	60
Zone-1, ^{o}C	229
Zone-2, ^{o}C	229
Zone-3, ^{o}C	229
Zone-4, ^{o}C	229
Nozzle, ^{o}C	229
Screw Stroke, mm	183
Cycle Time, sec	22.0, 18.0

Table 3. Molding Conditions.

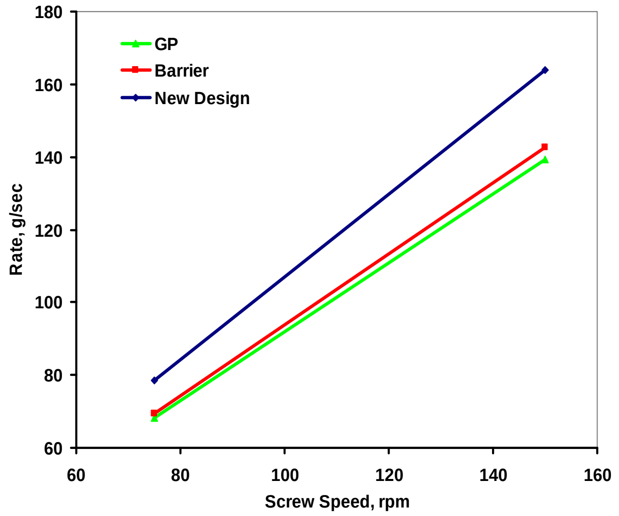

Figure 5. Screw Recovery Rate.

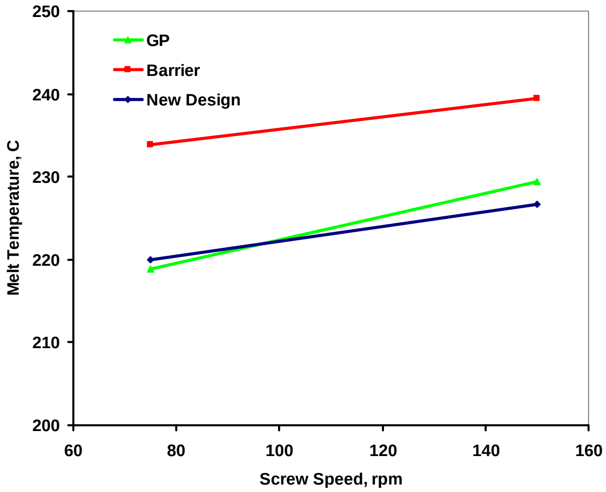

Figure 6. Discharge Temperature.

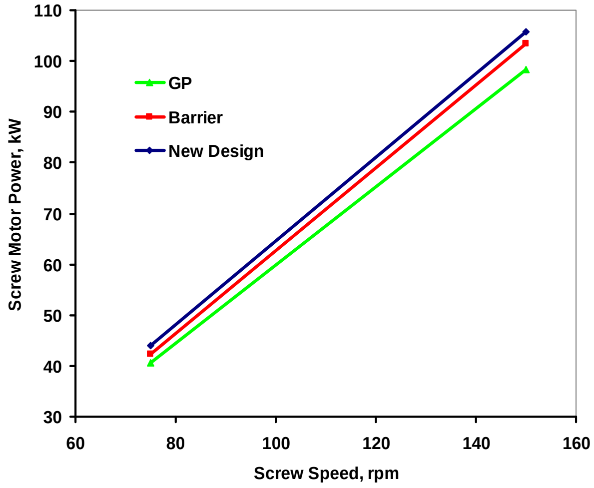

Figure 7. Screw Motor Power required.

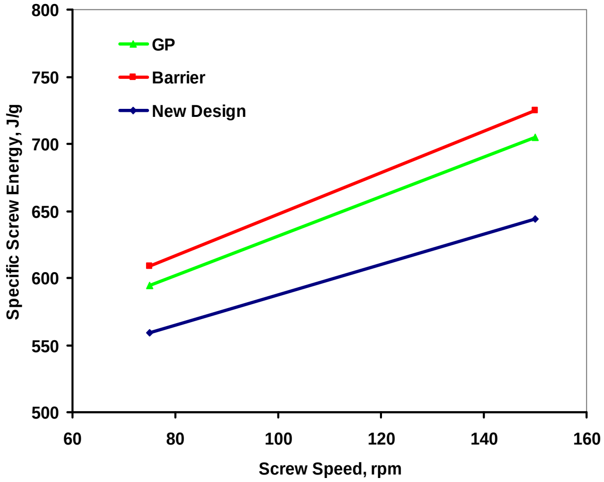

Figure 8. Specific Energy inputted by the screw.

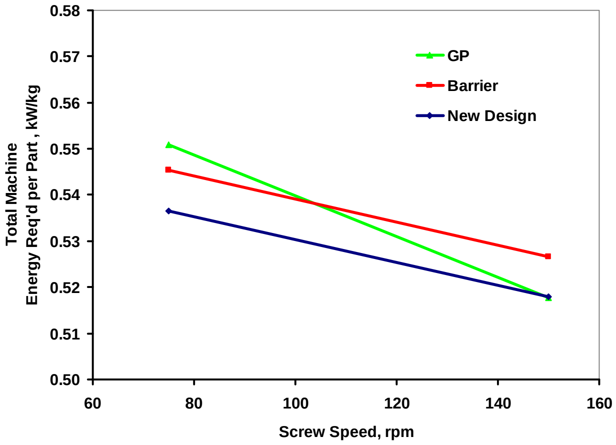

Figure 9. Total machine Energy required per molded part.