Melting Mechanism of a Starved-Fed Single-Screw Extruder for Calcium Carbonate Filled Polyethylene

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A study of starved-fed single screw extrusion was initiated to understand the relation between its distinctive melting mechanism and the improved mixing capabilities attained during compounding of a calcium carbonate filler into HDPE. Experiments were carried out in a 63.5 mm single screw extruder, examining the effect of degree of starvation on a conventional and barrier feed screw. Interest was focused on the mixing/melting mechanism of starved-fed solids-conveying as it affects the size and number of filler agglomerates observed in the extrudate. The melting performance of both feed screws was examined using pressure and temperature measurements down the screw length as well as direct inspection of the polymer in the screw channel via rapid screw cooling. Both screws showed improved mixing quality with increased starvation.

INTRODUCTION

Economical and technological forces are extending and diversifying the application of plastics in modern products and consequently requiring increased usage of solid and liquid additives (1, 2). Typically, several additives are combined together with a plastic for a specific process, with choices ranging from a multitude of categories including fillers, plasticizers, reinforcing agents, lubricants, blowing agents, flame retardants, stabilizers, etc. The effectiveness of any of these additives within an intended product depends on their homogeneous dispersion within the polymer matrix. Thus, the efficiency of mixing becomes a defining issue, as most of these additives are immiscible within a polymer. To enhance the capabilities of single-screw extruders for more effective mixing, vented extruders are being requested with longer L/D ratios and more sophisticated mixing devices are being introduced to the industry. The purpose of these mixing devices is to introduce greater-than-linear mixing to the otherwise linear mixing inherent of helix-in-a-helix flow within a single screw extruder. In the case of mixing solid additives into a polymer, it has been noted by several authors (2–4) that once agglomerates are formed, it is unlikely that the mixing behavior of an extruder can overcome their binding forces, even within an intensive mixing zone. Gale (3) stated that the most appropriate means of avoiding agglomerates in the product of an extruder was to prevent their formation. Observations made in experimental trials by the present authors, showed that both barrier and conventional screws provided a significant reduction in the size and presence of powdered agglomerates when the extruder was starved even by a small amount (5–20% starvation). The present work attempts to understand the mixing/melting mechanism of starved-fed solids-conveying and the manner by which powder agglomerates are reduced in size and number.

General understanding of the mechanisms for solids-conveying and melting in a flood fed plasticating extruder has been well developed since the early experimental work of Maddock (5) and Street (6). Solids-conveying prior to the onset of melting has been determined to be frictional force dependent, changing to a viscous shear dependency with the beginning of a melt film (7, 8). The model of Darnell and Mol (9) represents one extreme of the transition taken by the solid bed, attempting to explain the conveying of solids in the absence of melt with the assumption of a constant bed velocity. Chung (8) modeled the opposite extreme, looking at a solid bed reliant on viscous shear forces for movement. The melt film which forms adjacent to the barrel surface generally maintains its thickness by balancing melting rate and drag-induced flow, accumulating as a melt pool on the advancing-side of the flight once the pressure at this location exceeds the yield forces of the compact solid bed. The pressure measured over the solid bed is an indicator of the shear stresses and hence indicates the contribution of viscous heating to the melting rate (10). In studies on the formation of agglomerates with calcium carbonate ($CaCO_3$), Gale (1) observed from screw push-outs that in the early stages of melting, the powdered additive

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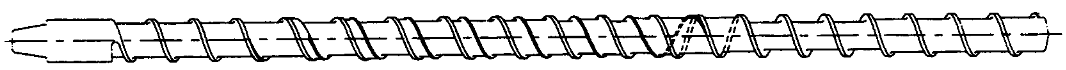
interfered with the normal melting behavior of plastic pellets. The powder reduced the transfer of frictional forces to the solids they coated, thus interfering with the formation of melt at the barrel surface. In addition, for polymer/filler systems, melting has been observed to occur in the absence of a melt pool thus deviating from the classical melting behavior. The following points were observed by Gale (1): i) sintering of solid mass began at the barrel surface and spread towards the screw root with the surface skin polished with large patches of segregated filler; ii) plastics granules were separated from each other by a coating of filler, with pockets of filler dispersed in this matrix. Heating by conduction from the barrel and the screw appeared to play an important role in the melting observed by Gale (1). The powdered additive filled the interstitial holes existing between the pellets of plastic, compacting under the applied shear stress to the solid bed, to form agglomerates (1, 3). In order to avoid the formation of agglomerates as suggested by Gale, a manner of controlling the feeding and melting mechanisms is therefore required to prevent or reduce the compaction of the aforementioned powder.

Starved feeding, prevalent in twin-screw extrusion, is rarely used in single-screw extrusion for its disadvantages and those studies examining starved feeding have done so in conventional metering screws solely. Operating at less than flooded conditions infers that the process is producing below its full capacity and can introduce undesirable fluctuations within the product in the machine direction. These fluctuations come from variances in the machinery controller units and the necessary additional equipment (i.e. gravimetric or volumetric feeders) now required to meter solids into the extruder. Despite these possibly significant disadvantages, starved-fed solids-conveying has been noted (11–13) to offer several advantages that improve the extrusion performance of several resins with either thermal sensitivity, difficulty in feeding, very high molecular weights or low friction. Generally, starved extrusion allows a wider variety of polymers to run within a single "screw design," particularly in vented two-stage designs where vent-flow is typically problematic. The throughput becomes another degree of freedom to be controlled in the process under starved conditions. At moderate levels of starvation (and being dependent on the polymer), researchers (11–14) have observed faster melting rates, improved venting of volatiles, lower die fluctuations, and reduced instances of solid bed breakup than under flood-fed conditions. However, these advantages were found in the extrusion of pellet/granular solids; powders demonstrated poor processability under starved-fed conditions for the same grade of resin (14). Experimental studies of polyethylene, polystyrene, and polypropylene homopolymer (12–14), and styrene-acrylonitrile copolymer (11) at degrees of starvation ranging from 0% to 50%, have been carried out in a variety of single-stage and two-stage conventional screw designs. These experiments documented the fluctuations and nominal values of pressure and melt temperature, as well as torque demand. Specific to each resin, reduced pressure fluctuations in the extrudate were found over a limited range of starvation starting from the flooded condition (11, 12, 14).

Isherwood *et al.* (14) examined the unique melting mechanism under starved-fed conditions through screw push-outs of polypropylene. The polymer had been coated with a small concentration of carbon black at the feed section of the extruder, to distinguish melting via conduction opposed to shear heating. Melting was delayed according to the degree of starvation until a solid bed could form, with initiation increased by approximately one turn for every 2% starvation (14) up to 10% after which the onset remained constant. Delayed compaction of the solids was due to the loose particulates originating from the feed section, requiring greater distances to develop the necessary frictional forces to fill the channel. The authors noted that the air phase seen in the early stages of solids conveying reappeared between the solid bed and retreating-side of the flight with the introduction of melt as the solid bed presumably began to compact and squeezed out the air. The air phase remained upon completion of melting, removed once the effect of back pressure from the die became significant. Of particular interest to this present work was the observation made by Isherwood *et al.* (14) that while the initiation of melt was delayed, the completion of melting corresponded to the flood-fed process. The rapid melting rate they observed contradicts the knowledge that there would be reduced heat transferred to the polymer from viscous dissipation due to the loose solids not forming a solid bed until melting began. The postulated reasoning for the rapid melting according to Isherwood *et al.* (14) was inter-particle friction resulting from the loose nature of the solids prior to forming a solid bed. Increased particle collisions between the solids should subsequently generate heat in the bulk of the polymer more efficiently than conduction and viscous heating could for a tightly confined bed. The greater mobility of the solids in the conveying zone has also been linked to greater mixing of blends or additives prior to melting. From measurement of the relative solid bed velocity made with polystyrene, it was found (14) that unlike flood-fed extrusion where the solid bed experiences a slow, steady acceleration, in starved-feeding the solid bed appeared to de-accelerate and then accelerate only after compaction. Modeling the observed melting mechanism and throughput under starve-fed solids-conveying, has generally been done through minor modifications to the equations applied to flood-fed extrusion (13, 15). These equations have qualitatively followed the trends observed experimentally. Campbell *et al.* (16) focused on the actual conveyance of the solids themselves, in the absence of melting or downstream effects, through observation of solids in an unheated glass barrel extruder. Through consideration of gravitational forces and the introduction of a normal force related to frictional forces exerted by pellets on the



Two-Stage DSB Barrier Screw

Two-Stage TSM Conventional Screw

TSM							
	FEED	TRANS	METER	TRANS	VENT	TRANS	METER
L/D	4.5	5	6	½	2	2	9
Depth (mm)	12.7		3.3		12.7		6.35
DSB							
	FEED	BARRIER		TRANS	VENT	TRANS	METER
L/D	4.5	11		½	2	2	9
Depth (mm)	12.7	S/C†: 12.7 – 1.27 M/C‡: 3.8 – 4.8			12.7		6.35

† S/C – Solids Channel
‡ M/C – Melt Channel

Fig. 1. Screw designs for the conventional and barrier screws.

barrel, the authors proposed a model that did not rely on pressure, unlike the model of Darnell and Mol (9) for solids conveying.

The purpose of this study was to develop an understanding of the melting mechanism involved with starved-fed single-screw extrusion in the compounding of a solid powder into a plastic. Starve-feeding was used to control the feeding and melting characteristics of the process and thereby reveal the important conditions necessary to reduce the size and number of agglomerates within the extrudate.

EXPERIMENTAL

Materials

The base resin was Petrothene LR-7320, a 0.3 MI blown-film grade HDPE, received in pellet form, supplied by Equistar Chemical. For analysis of mixing performance, calcium carbonate (surface-treated $CaCO_3$, 1.4 μm average diameter supplied by OMYA, Inc.) was added at 20 wt% with the base resin to the feed section of the extruder. Melting analysis was aided by the addition of pre-compounded pellets with 5 wt% carbon black in a HDPE carrier added just prior to crash-cooling the extruder.

Equipment

The experiments were performed on a 63.5 mm 30:1 L/D water-cooled Thermatic™ single-screw extruder fitted with two K-Tron loss-in-weight feeders for the HDPE pellets and $CaCO_3$ powder. Seven Dynisco pressure transducers along the extruder length and one at the die were used to measure the pressure profile and process stability. The melt temperature was measured at the die using an exposed-junction variable-depth thermocouple which had been adjusted to read at the center of the melt stream. The pressure transducers were located along the barrel at 5.64D, 8.48D, 11.3D, 14.13D, 19.75D, 25.5D, and 29.1D as measured from the flight pocket and denoted as. P-1 through P-6 and P-BP (breaker plate) respectively. The extrudate was stranded and pelletized for later microscopic analysis.

Two screws were used in this experiment as shown in *Fig. 1*. The first screw was a two-stage conventional screw with a 4.5D feed zone and 5D transition. The remainder of the screw was divided amongst the two metering zones and the vent section. The second screw was a standard two-stage moderate intensity (regarding its melting/mixing capabilities) DSB™ barrier screw with a 4.5D feed section and a barrier before the vent zone. The second stage was identical for the two screws. Neither screw possessed a mixing section, in order to evaluate the mixing attributed to the starved-fed solids-conveying mechanism.

Procedure

A reverse barrel temperature profile was consistently used for all experiments: 218-204-190-190-190°C and 204°C at the die. Runs were performed at five different degrees of starvation (0, 5, 10, 15 and 20%) for two screw speeds of 50 and 75 rpm. The degree of starvation (S) was defined as:

$$S = 100 \cdot \left(1 - \frac{Q_s}{Q_f}\right) \quad (1)$$

where Q_s is the mass throughput rate under starved conditions and Q_f is the flood-feed mass throughput rate. Pressure and melt temperature data were collected for both screws mentioned above, on a high-speed data acquisition unit at 100 Hz per channel. Screw push-outs were done at 0% and 15% starvation for both screws at 50 and 75 rpm, by crash cooling the extruder barrel and screw itself followed by extraction under hydraulic force. The screws were pushed out into a clear cast-acrylic tube with a nominal inner diameter matching the screw, so that no information would be lost concerning the solids-conveying section.

Analysis

The melting mechanism of the starve-fed extruder was determined from the pressure and temperature data, and from cut cross sections of the solidified polymer every half turn of the screw. Analysis of mixing performance was done on samples of the extrudate taken at each degree of starvation. Qualitative analysis was conducted under an optical microscope (at 28× magnification) to determine the dispersion of the $CaCO_3$ filler.

RESULTS AND DISCUSSION

Two different screw configurations typically used in the industry were tested, namely a conventional and a barrier screw, to evaluate their performance under starved-fed conditions. Because of the inherent differences between the barrier and conventional screw types concerning balancing of the two-stages in a vented screw design, as well as residence time and shear history, extrapolating the results to indicate a preferred screw type for mixing based on starved-feeding is beyond the scope of this work. Specific throughput ranged from 1.2 to 0.9 kg/h/rpm for the barrier screw, while the conventional screw gave 0.8 to 0.6 kg/h/rpm as the degree of starvation increased from 0% to 20%. In addition, solid bed breakup was observed only in the conventional screw, which complicated the pelletizing operation of the extrudate owing to gross fluctuations in rate in the machine direction. A full set of experimental data taken when the extruder operated at 0% and 15% starvation for the two screws, is shown in *Table 1* (noting that P-BP indicates pressure at the breaker plate). Trends seen in *Table 1* shall be discussed in a later section. The following section discusses the quality of mixing obtained by the two screws at different degrees of starvation.

Qualitative Analysis of Mixing

The mixing quality was determined from hot-pressed film samples under a microscope. Photographs of the samples observed under magnification are presented in *Figs. 2* and *3*. As the samples were viewed with transmitted lighting under the microscope, the calcium carbonate agglomerates appeared as black domains within the polymer.

As the degree of starvation was increased, the agglomerate size decreased markedly from the flooded condition, eventually yielding a product with virtually no calcium carbonate particles distinguishable at 20% starvation. The samples from the barrier screw showed reduced agglomerate sizes similar to those from the conventional screw with increasing starvation and were comparable in size and number at both screw speeds examined. Generally, significant changes in mixing occurred between 0% to 10% starvation, with only minor differences noted in the samples at higher degrees of starvation.

Figure 2 shows photographs of the samples under magnification view, taken from both screws when the extruder operated at 50 rpm. The particle size changed from 340 μm at 0% starvation to 60–90 μm at 10% starvation and eventually diminishing to a non-quantifiable value by 20% under current magnification. At 75 rpm (*Fig. 3*), an average particle size of 215 μm was measured for 0% starvation, diminishing to 70 μm at 10% starvation. Comparison of the particle sizes for each level of starvation at the two screw speeds indicate that increased shear did reduce the domain size of the agglomerates, but clearly the effect was relatively minor compared to the effect of starvation. The difference at 75 rpm, which was not seen at the lower screw speed, was an increase in particle size to 160 μm at 15% for the conventional screw. The agglomerate size was similar to the flooded condition, presumably due to surging. Sampling was not possible for the 20% starved level in the conventional screw due to excessive surging of the output.

Table 1. Measured Process Variables at Flood-Fed and Starved-Fed Extrusion.

	Conventional Screw				Barrier Screw			
Starvation	**0%**	**0%**	**15%**	**15%**	**0%**	**0%**	**15%**	**15%**
RPM	50	75	50	75	50	75	50	75
KG/HR	40.0	62.6	34.0	53.3	62.2	91.1	50.7	77.0
KW	6.2	8.9	3.6	6.2	6.3	11.9	5.6	8.9
KG/HR/KW	6.5	7.1	9.5	8.6	9.2	7.7	9.0	8.7
KG/HR/RPM	0.8	0.8	0.7	0.7	1.2	1.2	1.0	1.0
TORQUE (kN·m)	7.4	9.5	4.3	5.0	7.6	12.7	6.8	9.5
P-BP (MPa)	14.92	14.33	8.62	13.20	16.58	22.43	9.13	10.29
MELT TEMP(°C)	216	218	214	219	209	216	206	210

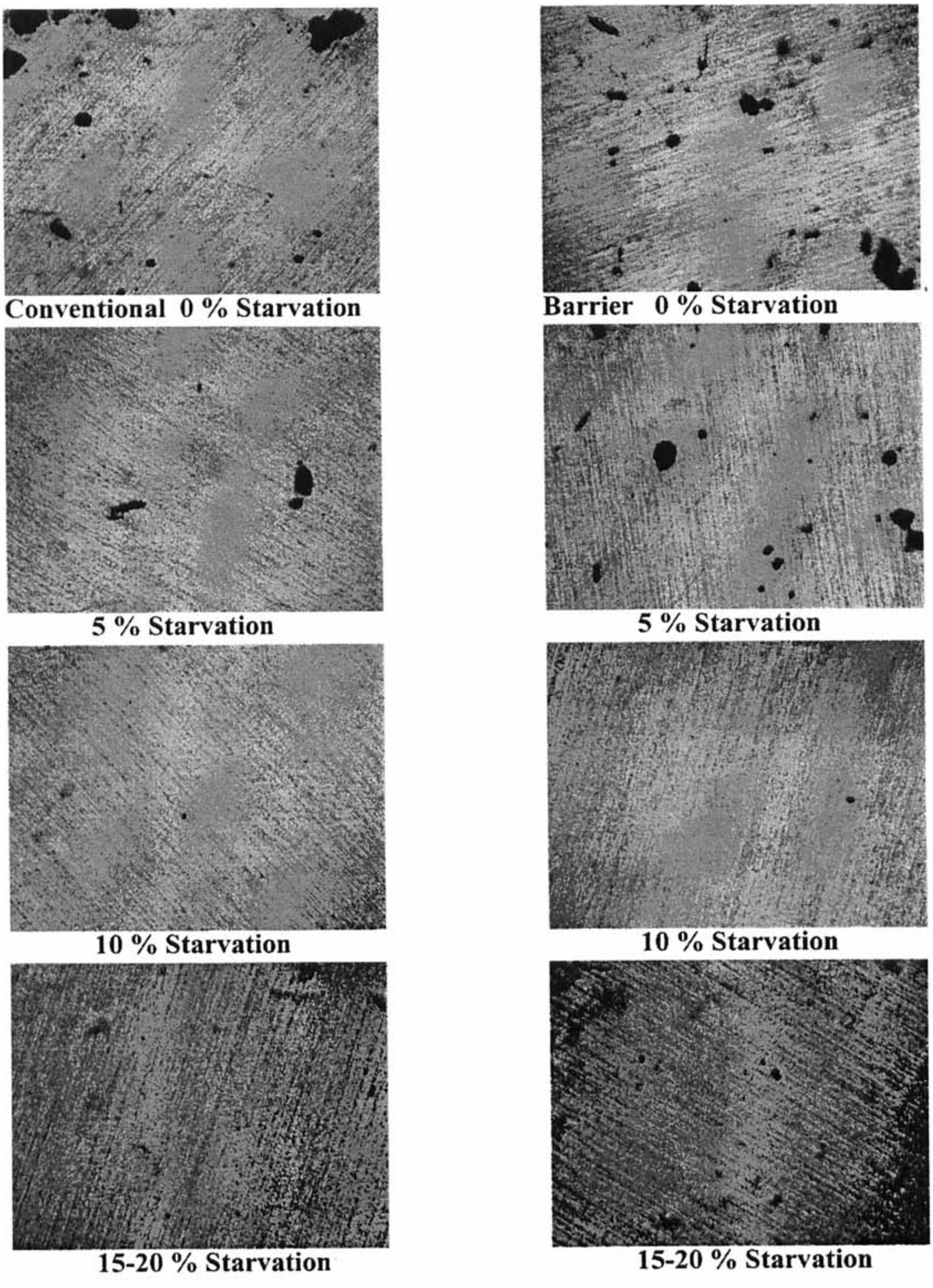


Fig. 2. Microscopic analysis of the samples taken from both screws at 50 rpm.

Effect of Starvation on the Pressure Profile, Torque and Melt Temperature

The nominal pressure values measured at each pressure transducer were plotted in *Fig. 4* to show the axial profile for each degree of starvation at 50 rpm. Zero pressure measurement at P-1 was expected with increased degrees of starvation for both screws as the formation of a solid bed would be delayed. However, under flooded operation the measured pressure at the first transducer remained near zero for the two screws, presumably because the calcium carbonate interfered with solid bed compaction. At the die, the nominal head pressure (P-HD) was constant with increasing degree of starvation for both screws. The vent was located

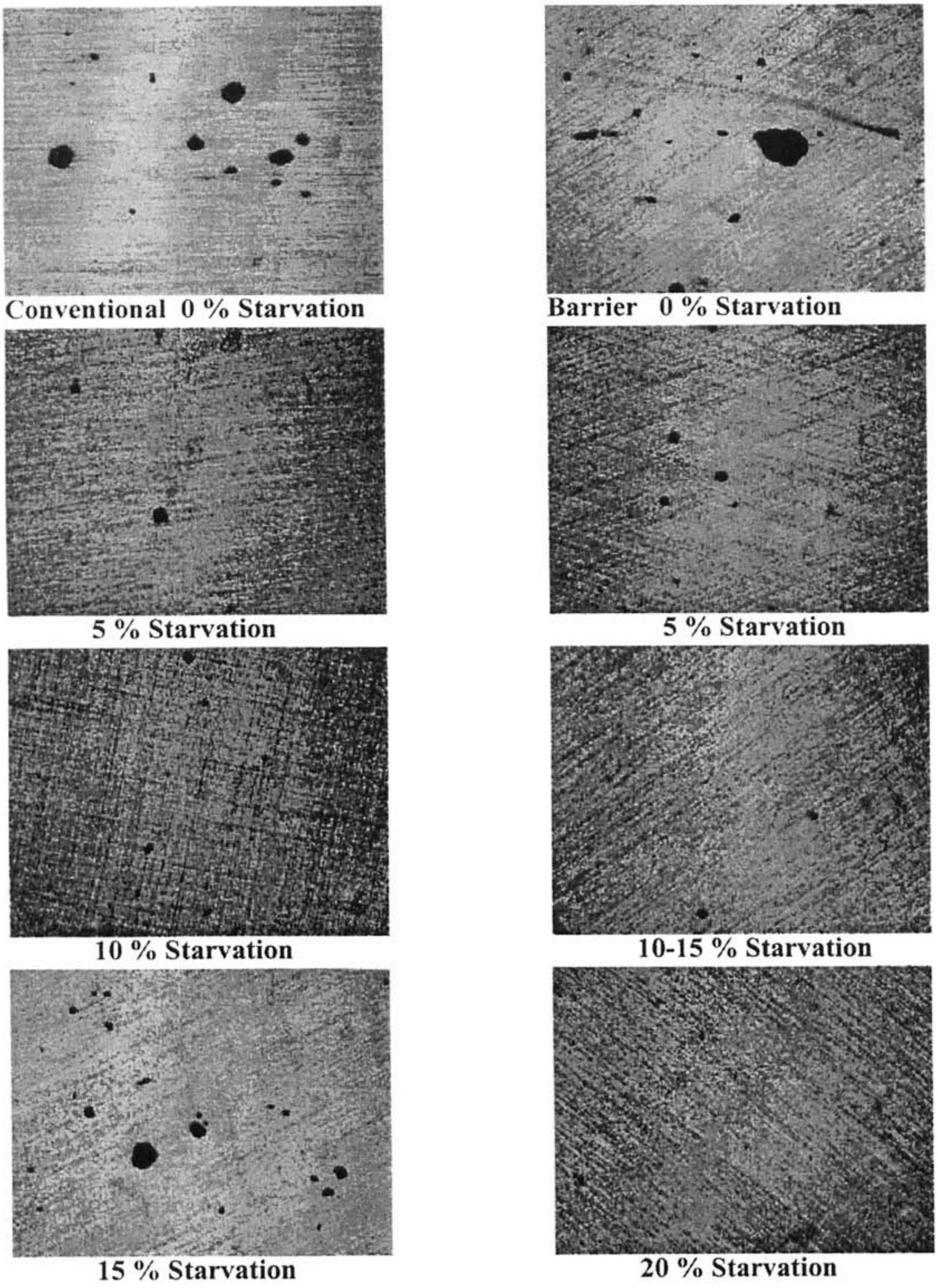


Fig. 3. Microscopic analysis of the samples taken from both screws at 75 rpm.

immediately after P-4, which was the reason for the low pressures observed at not only P-4 but also P-5. The comparatively high pressure seen at P-5 for the flooded case in the conventional screw and both the flooded and 5% starved case for the barrier screw is indicative of the observed vent flow condition. Vent flow resulted from an imbalance in the pumping capacity between the first and second stage of the screws. No vent flow was seen beyond the conditions noted. Overall, the performances of the two screws were similar with respect to their pressure profile, with only minor differences noted. In the case of the barrier

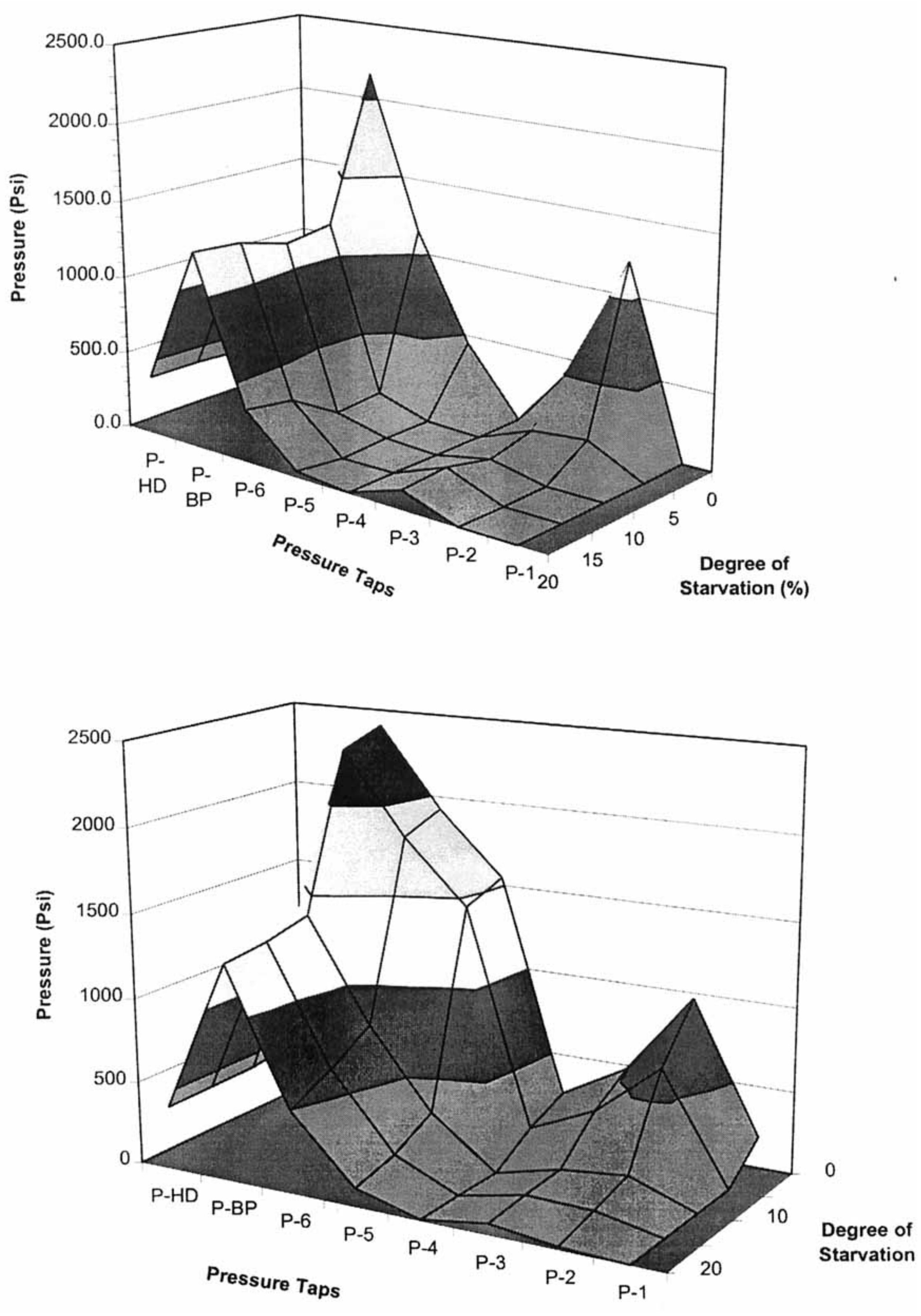


Fig. 4. Effect of starvation on the axial pressure profile in the conventional screw (top) and the barrier screw (bottom).

screw, pressures at 5% starvation did not drop as significantly as seen in the conventional screw. The microscope samples in *Fig. 2* showed that the reduction of agglomerates in the barrier screw was not as great as seen in the conventional screw for the 5% starvation/50 rpm condition. For both screws, the pressure values had reached their respective minimum by 10% starvation, which coincides with the range of 0–10% starvation that was noted to yield the greatest change in mixing according to the microscopic analysis. For other conditions where the pressure profiles were similar, the extent of mixing was likewise similar. Since this data point appears to show the only major difference between the two screws, it is likely that the reduction of agglomerates is related to the lower pressures over the screws and not shear effects caused by the difference in screw design.

The nominal melt temperature showed a drop at the onset of starvation, with little change over the range of 5–20%. The difference between the two screws was 5°C, being larger for the conventional screw. *Table 1* shows that the difference between 0% and 15% starvation was at most 6°C, being largest for the barrier screw and at the higher screw speed of 75 rpm.

Figures 5 and *6* show the effect of starvation on the torque and power efficiency at 50 and 75 rpm for the two screws, respectively. The torque followed the same trend in decreasing values with increased starvation as shown in *Fig. 4* for the pressure gradients. As expected, increasing screw speed increased torque and with barrier screws the torque demand was greater compared to the conventional screw. The power efficiency (kg/h/kW) data shown indicates that there was less power consumption at higher degrees of starvation, reaching a maximum at 10% starvation, then decreasing slightly. This trend corresponds closely with the decrease in pressure, which is a measure of the shear stress over the resin as it is melted and conveyed. The correlation of lower torque and shear stress with improved quality of mixing suggests that the mechanism by which agglomerates are reduced in size and number is not related to inter-particle friction but rather improved solids mobility brought about by less bed compaction. The trends seen in torque and power efficiency were also observed by McKelvey (11), who noted that such trends demonstrate the advantage of operating under starve-fed conditions particularly for polymers that are sensitive to viscous heating.

Melting Mechanism for Starved-Feed Extrusion

With the screw being pushed out into a clear cast-acrylic tube, both loose solids and those parts melted together could be observed as they existed within the extruder. After visual observation of the screw, the loose solids were discarded and the carcass was cut from the screw at every 1/2 turn. With rapid quenching of the polymer from the barrel wall and screw root, the maximum cooling was applied to minimize the amount of material melted via conduction once the screw was stopped. The inclusion of calcium carbonate lowered the friction of the polymer against the barrel, allowing the screw to be pushed out with little heat or force applied, and therefore, concerns over axial load disturbing the frozen plastic carcass were unwarranted for the filled samples. The carbon black masterbatch was added at 1% loading to the feedstock prior to shutting down the extruder. The inclusion of trace amounts of a colored plastic provided a means of distinction between melt produced by either shear heating or conductive melting of the solids. When melting was shear-dependent, the colored material produced striations in the newly formed melt, while melting by conduction maintained the color within the confines of the original space taken up by the pellet. Differences

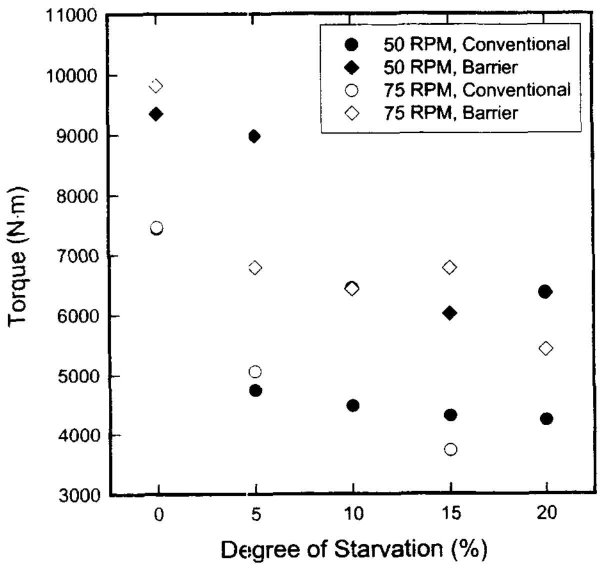


Fig. 5. Effect of starvation on the torque demand for both screws.

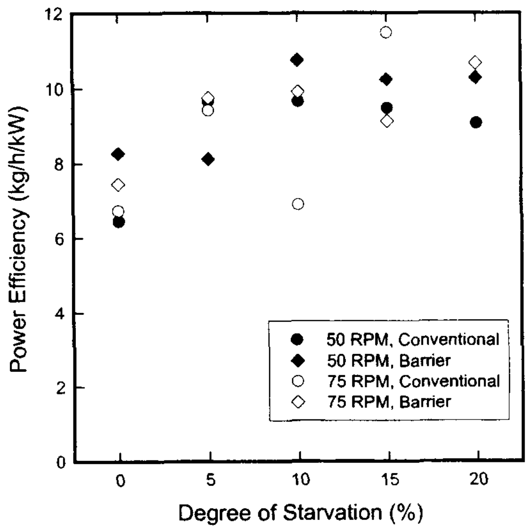


Fig. 6. Effect of starvation on the power efficiency of the two screws.

in the melting behavior between starved and flooded conditions were sought to derive an understanding of the mechanism involved in melting when the channel was not fully filled and what impact the calcium carbonate filler contributed to the new melting mechanism. It was hoped this analysis would determine the circumstances that resulted in the filler agglomerates being reduced in size and quantity.

Screw push-outs from trial runs at 50 rpm using only HDPE without calcium carbonate were in agreement with the previously mentioned results of Isherwood *et al.* (14), showing that the classical melting mechanism observed with the flood-fed screw breaks down with the introduction of starvation. For the starved case (15%) with only HDPE, an air phase next to the retreating flight was observed comprising 50% of the channel once a melt film had formed, which decreased to 15% upon completion of melting. Owing to the open-discharge nature of the first stage of a vented screw, subsequent filling of the channel was not observed until the second stage. Melting by conduction was dominant with the melt film above the solid bed thickening over an axial distance accounting for 50% of the melting length. A melt pool was observed in the latter half of the melting zone, accounting for only 5% of the channel cross-sectional area. Streamlines of color close to the root of the screw showed evidence of a minor solid bed velocity vector towards the retreating flight of the channel. The melting length from the formation of a melt film to the completion of melting was four turns at 15% starvation, compared to eight turns under flooded conditions. Subsequent push-outs discussed will examine the effects of filler, screw rpm and starvation on the melting mechanism.

Different from the observations made for the melting of non-filled HDPE, both starved- and flood-fed screw push-outs yielded similar observations concerning the melting mechanism when calcium carbonate was present. Essentially, the only distinct differences in melting noted between the flood-fed case and the starved case were the start position and length of the melting zone, at least for the slower screw speed (i.e. 50 rpm). For the 80/20 HDPE/$CaCO_3$ feed under starved conditions, no air phase next to the retreating-side of the main flight was observed in the melting region as noted in the case of the non-filled HDPE. To clarify, no further mention of the case with non-filled HDPE will be made in this discussion. General observations on the melting mechanism from the experimental trials from both flood-fed and starve-fed operating conditions with 20% $CaCO_3$ were:

- Greater coating of the polymer solids with filler for the 15% starved condition compared to the flood-fed. Excess filler was found at the root of the channel before melting began.
- A melt film formed next to the surface of the barrel with a melt pool beginning on the advancing-side of the main flight approximately 1/4 turn from the onset of melting. In the barrier screw, this 1/4 turn represented the time taken before the melt entered the melt channel. The melt pool grew slowly in both screws.
- The barrier screw most clearly showed filler striations in the melt pool, demonstrating helix-within-a-helix melt flow. Fine agglomerates of filler were seen in the melt pool, which increased in number and moderately in size with increasing distance from the onset of melting.
- Melt films were also seen at the retreating-side of the main flight and at the screw root. Examination of the striations formed in the melt film at the bottom of the screw channel indicated motion of the solids over this film in the down-channel direction. The film at the flight gave evidence of growth, presumably from conduction across the flight wall.
- Two turns from the start of melting, most of the solid bed had sintered together and formed a compact mass with a small number of pockets of filler seen in the matrix and no filler found on the screw root. Only a small fraction of the solids remained loose next to the melt pool or on the advancing-side of the barrier flight.
- In the case of the conventional screw, there was evidence of solid bed breakup occurring, with melt penetrating into the bed near the center of the channel or completely separating the bed into islands of solids.

For each screw at 15% starvation, the beginning of sintering corresponded to approximately 70% filling of the channel with the semblance of a solid bed forming. Prior to that point, the solids filled only 20–30% of the screw channel, residing at the bottom of the barrel bore. Once adequate pressure was developed in the solids channel, the solids began to form a bed, thus improving contact at the barrel surface with the loss of chaotic re-orientation. The screw channel became completely filled with the solid bed immediately before the onset of the melt film. Initial sintering of the polymer/powder system took place next to the barrel surface for either screw corresponding to the initial tapering of the channel cross section. In the barrier screw, some solid pellets were observed to have entered the melt channel of the barrier screw (as depicted in *Fig. 7*), since no melt film had formed yet to prevent such an occurrence. All screw turns were completely filled with solids in the case of flood-fed extrusion as expected prior to melting.

In general, for flood-fed solids-conveying, the mechanism of Archimedean transport was insignificant, being seen only under the hopper where there was essentially an absence of pressure (17); the models of Darnell and Mol (9) and later Chung (10) tend to describe the mechanism of transport appropriately in this case. For starved-fed solids-conveying, the mechanisms appear to be different from the flood-fed case, with the solids initially conveyed via Archimedean transport for

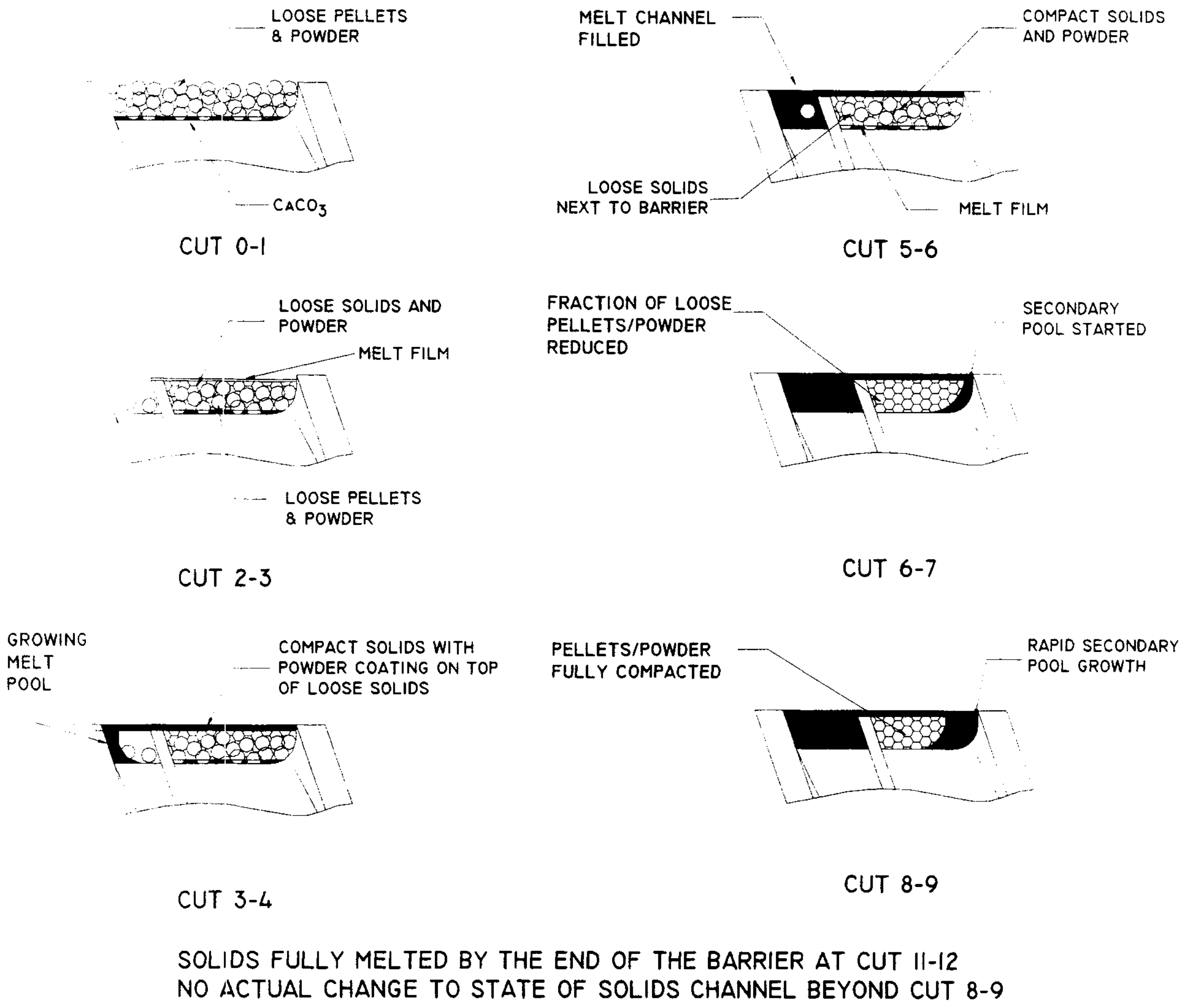


Fig. 7. Channel cross-section in the melting zone of the barrier screw at 15% starvation and 50 rpm.

an extended distance prior to the onset of a solids bed and melting at the barrel surface [namely, the Chung (10) model]; the model of Darnell and Mol (9) does not appear to have proper application in the case of starvation.

From the observations of the melting zone for the two screws at both 0% and 15% starvation, it had been noted that the sintered solid mass began at the barrel surface and then spread towards the screw root and away from the retreating-side of the main flight. The pellets were coated with filler, with the remaining calcium carbonate located at the screw root as a bed. *Figures 7* and *8* depict what was observed in the channel cross sections taken from both screws at 15% starvation and 50 rpm once the solids began to sinter together. Changes in the channel depth were neglected from the *Figures* for clarity. *Figure 8* shows evidence of solid bed breakup in the conventional screw as melt impinges into the solid bed, which complicated determination of the actual melting length of the HDPE/$CaCO_3$ mixture. *Figure 9* traces the decrease in the solid bed width within the conventional screw for both 0% and 15% starvation; deviation from a smooth trend as the width of the solid bed decreased was attributed to solid bed breakup. The *Figure* also demonstrates the rapid melting inherent to starved-feeding, since the onset of melting was significantly delayed in comparison to the flooded case, yet it finished at the same location. No solid bed breakup was observed within the barrier screw owing to its controlling geometry over the solid bed, which prevented the melt pool from remaining in intimate contact with the solids. However, the barrier screw also maintains a consistent end to the solid bed, making the onset of melting as the only difference that may be observed between the two modes of feeding. Consequently, including the decrease in the solid bed width within the barrier screw in *Fig. 9* would be meaningless.

At a screw speed of 50 rpm, the melting length at 15% starvation for both the barrier and conventional screw, covered only four turns from when the melt film was first observed. Flood-fed extrusion increased the

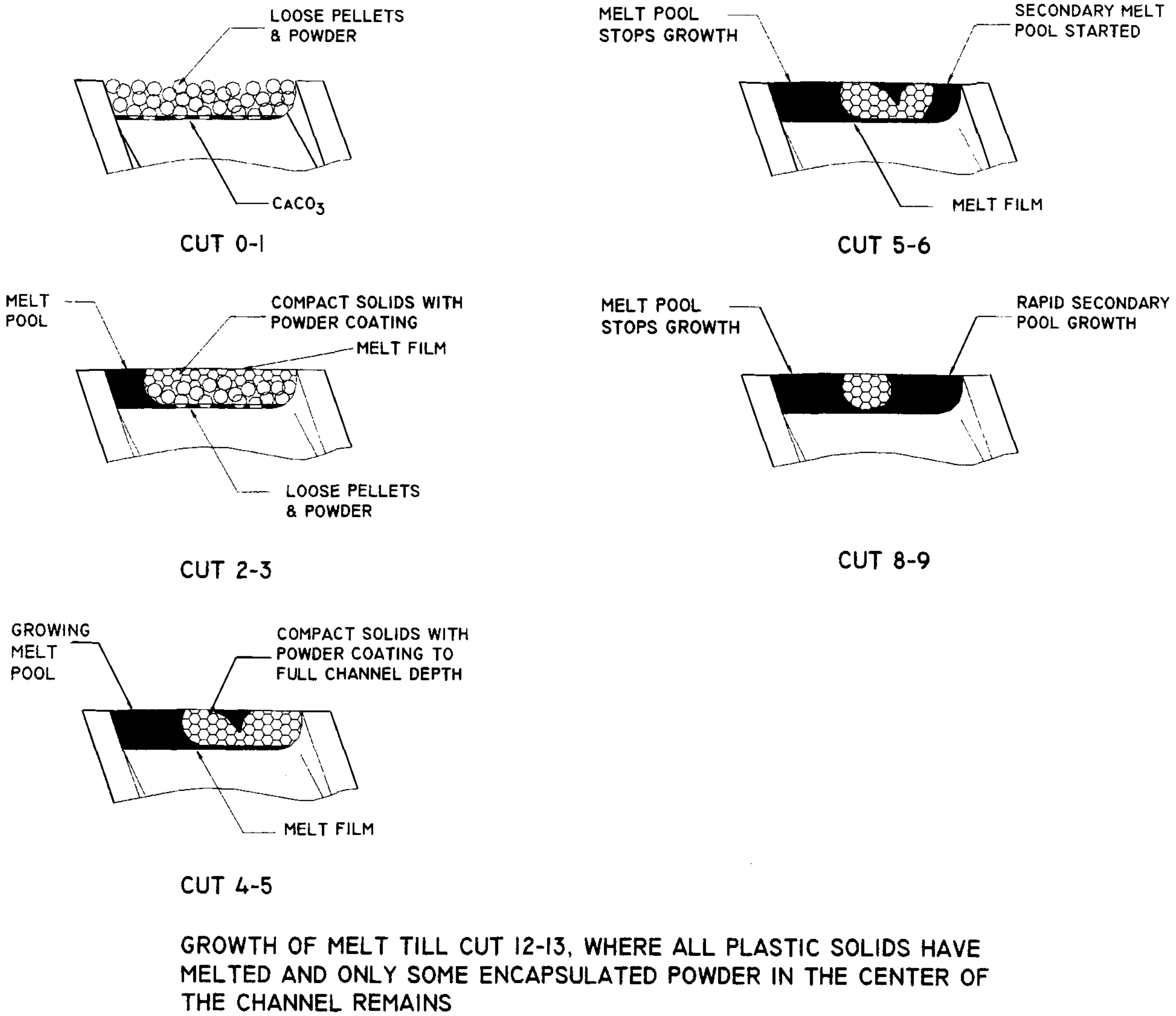


Fig. 8. Channel cross-section in the melting zone of the conventional screw at 15% starvation and 75 rpm.

melting zone to approximately eight turns. The solid bed exhibited the onset of sintering at the fifth turn of the screw from the shank for the conventional screw and at the fourth turn using the barrier screw for 15% starvation. The melt film began at the fourth turn for the barrier screw and at the fifth turn for the conventional screw. In comparison to the observations given for 15% starvation, under flood-fed conditions the onset of sintering was seen at the third turn for the conventional screw as well as for the barrier. The melt pool began one-quarter of a turn later once the melt film formed for all 50 rpm trials.

From screw push-out experiments at a screw speed of 75 rpm, which were done only on the barrier screw owing to excessive solid bed breakup in the conventional screw, both flood-fed and 15% starved conditions revealed similar initiation of the melt film at the sixth turn, one turn after the onset of sintering. The melt pool began at the eighth turn for both feeding conditions also, at which point the similarities ceased. With 15% starvation, the melt channel was filled with solids (pellets and powder) when the melt pool began, and approximately 20% of the channel remained filled with these solids at the end of the barrier section—far more solids in the melt channel than observed at 50 rpm. For the flood-fed case, the melt channel possessed only a few pellets upon initiation of the melt pool, which melted by the last three turns preceding the end of the barrier. It is the passage of solids into the melt channel under starved conditions (at both screw speeds) that may be responsible for the few agglomerates present early in the melt pool; the majority of agglomerates appear to form near the end of the melting zone.

The rapid melting rate seen under starved-fed conditions was explained by Isherwood *et al.* (14) as occurring through inter-particle frictional heating, though the source of such energetic interactions among the solids sufficient to cause heat generation for melting was never identified. An alternative hypothesis is drawn from the observations made within the present work.

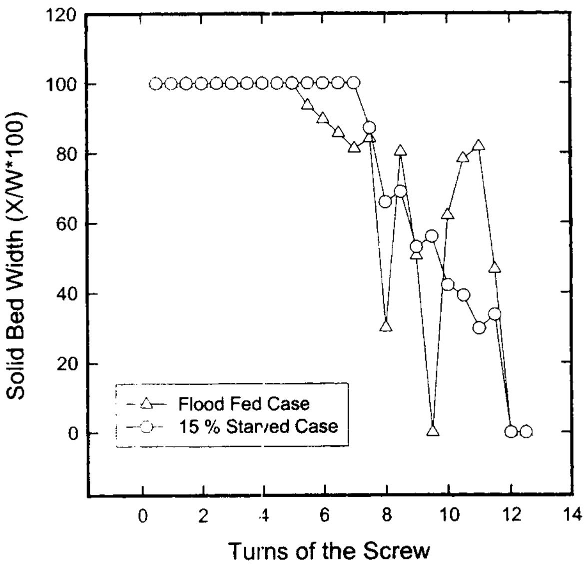
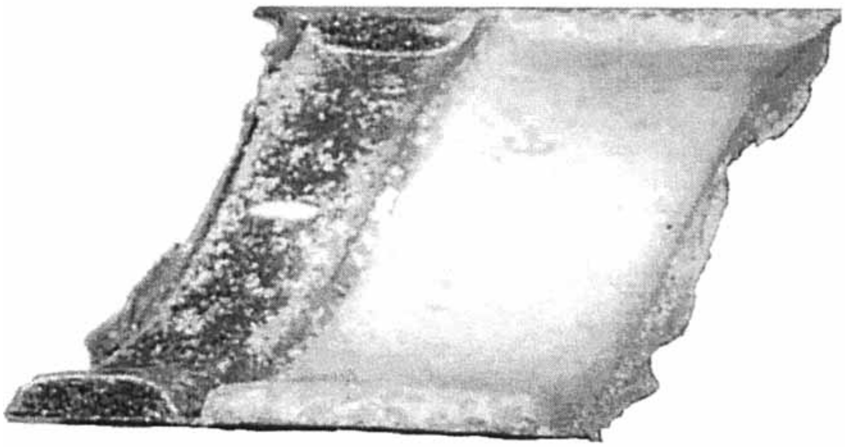
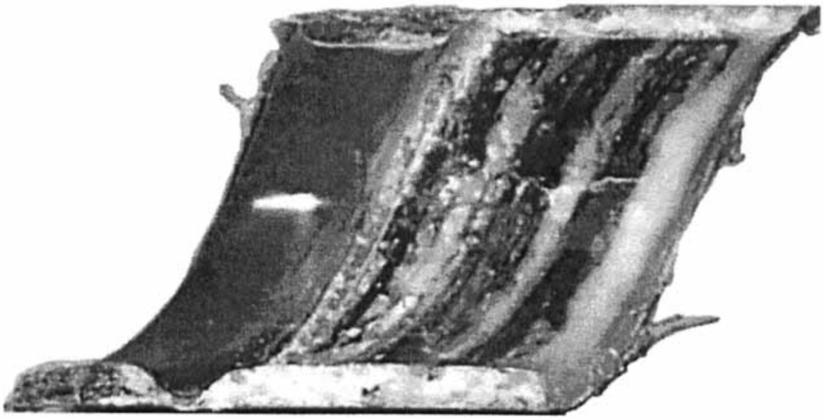


Fig. 9. Change in solid bed width axially down the conventional screw at 50 rpm for both flood-fed and 15% starved-fed extrusion.

At the initial channel fill of 20–30% solids, the solids are dispersed about the lower half of the extruder bore, making a relatively high contact area between the solids and the barrel surface. During that time, it would be reasonable to state, the transmission of conductive and radiant heat from the barrel surface to the polymer pellets would be relatively high. The rotation of the screw would provide conveyance of the material as well as some recirculation of the solids. All those pellets loose in the channel would receive significantly greater heating than in the form of a solid bed as would be the case under flood-fed conditions. According to Campbell *et al.* (16), with a channel at 50% fill, the solids begin to circulate over the screw root as the screw rotates, suggesting that the high transmission of heat to the solids continued, though likely at a diminished rate as the channel filled, possibly until the onset of melting was observed in our trial (i.e. 70% fill). Unfortunately, the locations of the pressure transducers used were insufficiently spaced over the axial length of the extruder to adequately reveal how the degree of channel fill changed down the screw. A measure of the degree of fill would give an indication of the length



Flood-Fed Screw Cut



15 % Starved-Fed Screw Cut

Fig. 10. Photographic evaluation of the flood-fed and 15% starved-fed extrusion conditions on the size of filler agglomerates within the screw channel of a barrier screw at 50 rpm.

of time to which the solids would have been exposed to the barrel surface in such a loose manner. Most significant from the pressure traces was the dramatic reduction of pressure at all transducer locations in the melting zone under starved conditions, which appeared to be related to the deagglomeration of the filler, as discussed below.

The presence of calcium carbonate agglomerates in the melt was seen under both flood-fed and starved conditions, though at 15% starvation agglomerates appeared to be lower in concentration and in size. The increased concentration and size of agglomerates observed in the screw cuts from the flood-fed case compared to the starved case are shown by photographs in *Fig. 10.* The photographs clearly show the undesirable mixing obtained under conventional flood-fed extrusion with respect to compounding filler at 20% into polyethylene. It was also observed from such screw cuts under starved operating conditions that the agglomerates appeared to be continually breaking apart (deagglomerate) under the shear stress of flow within the melt pool (or melt channel as was the case with the barrier screw). No evidence of agglomerate reduction was seen in the polymer cuts taken from the flooded screw. To account for the differences noted, the state of agglomeration under starvation was hypothesized to be linked to two factors. First, the greater heating of the solids prior to forming a solid bed allowed the pellets to soften sufficiently, which resulted in an improved coating over the pellets with powder prior to solids compaction. Hence, greater uniformity in the system from the start of the melting zone. Second, the weak binding forces on the agglomerates formed under starved conditions (which allowed them to disperse readily within the melt) was thought to be attributable to the low pressure and torque experienced by the solids, reducing the intensity of compaction on the filler (and pellets) during melting.

CONCLUSIONS

The quality of mixing with respect to filler dispersion was seen to improve with increased degree of starvation. A reduction in the number and size of agglomerates generated during melting with starved feeding was thought to result from several phenomena observed in the solids-conveying and melting zones. These were improved solids preheating due to the absence of a solid bed early in the solids-conveying zone coupled with improved filler coating of the pellets and lower intensity in the forces that result in solids compaction. Each factor contributed to the improved quality of mixing observed compared to flood-fed extrusion.

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