INVESTIGATION INTO A HIGH OUTPUT POLYPROPYLENE SCREW AND ITS MIXING MECHANISM

Keith Luker, Randcastle Extrusion Systems, Inc., Cedar Grove, NJ
Thomas M. Cunningham, Extrusion Technical Services, Brodheadsville, PA

Abstract

It is known, industry wide, that polypropylene (PP) resins plasticate at reduced rates compared to other olefins. While many causes have been suggested for this problem, a solution was not. A simple, spiral fluted extensional mixer (SFEM) was first introduced for the single screw extruder (SSE) for its superior compounding. [1, 2, 3, 4, 5]. A variation, the Elongator II, hereafter SFEM II, was tested against a control screw for output. A 100% increase in output was found over a conventional screw—more than making up for PP's historically low rate.

Because the SFEM series is noted for its ability to compound like a twin, we investigated mixing on the SFEM II. The investigation compares the flow to a simple computer model. A color concentrate of just 0.5% was used with frozen pullouts or carcasses showing the mixing during operation. The extrudate is examined and, even when magnified to 100X, does not show striation lines.

Introduction

Output: It is well known that PP typically has a low pound per hour output in the SSE when compared to other materials—even given its lower density. This has placed PP at a disadvantage compared to other materials, particularly the olefins. The reasons for the low output have been very well studied and summarized [6]:

> Cheng (1,2) used a barrier screw and several PP resins with different melt flow rates (MFR) and concluded that the PP melting rate was the controlling factor for the extrusion rate, and not solids conveying or the pumping rate. The high melting temperature, high crystallinity, low pellet compressibility, and low shear viscosity all contributed to the decrease in the PP melting rate. The lower shear viscosity in the operating range of melting was due to its high sensitivity to shear rate; i.e., shear thinning behavior. Steward and Bradley (3) further suggest that PP resins exhibit fairly poor solids conveying characteristics in addition to poor melting ability, and subsequently recommended a barrier screw to overcome these limitations.

The paper also says,

> Most extruder designers are aware of the decreased specific rates for PP resins. In general, they choose a barrel diameter that is one size larger than what would be required for the same rates using LLDPE resin.

So, this is very significant problem. Solving the problem means that smaller extruders may be used for higher PP rates and that existing extruders can produce more PP.

We believe that Steward and Bradley were correct in summarizing the general cause but not in their solution. Barrier screws are resistive to flow. The SFEM series is a naturally low resistance screw because the inlet channel, C1, is open down stream. By increasing the pitch of the first melting mixer, E1, the SFEM II was created with lowered resistance at the inlet as well. A comparative test of output was made between a conventional screw and the SFEM II.

Mixing: The SSE is an efficient and effective polymer melting and pumping device used in many processes, including injection and blow molding. One of the deficiencies of the SSE, until recently, is mixing. The plug flow nature of the SSE causes a narrow residence time distribution, so typically there is little back-mixing effect in a SSE [7]. The circulating flow in the screw channel causes a wide variation in the amount of mixing experienced by the polymer [8]. Often the mass is not completely melted until near the end of the screw allowing little time for mixing. Numerous mixing devices have been added to screws after melting in an attempt to improve the mixing. Intensive mixers typically reduce the output of the screw while increasing the polymer melt temperature, which can be undesirable.

SSEs capable of processing by use of repeated extensional flow fields can provide excellent melting and mixing with minimal heating of the melt. This has allowed even processing of rigid polyvinyl chloride powder at historically unheard of screw speeds. [9] Since the SFEM has twin like compounding in many applications [1, 3, 4], an initial study of the quality of mixing and of the fundamental mixing mechanism of the SFEM II is of great interest.

Materials

A blend that would highlight mixing effects was chosen—a 0.5% of a Navy Blue concentrate (Coloron, 25:1, Navy 60170, a pelletized styrene acrylonitrile) was added to natural polypropylene pellets (Sunoco Grade TI4005F, melt flow 0.5g/10min.). The formulation works

out to a 200:1 let down which is much more difficult to mix properly than the typical 25:1 letdown found in many applications. The materials were blended by hand shaking in a bag prior to extrusion and added to the extruder hopper (flood feeding). The materials were not dried.

Equipment

A 25mm horizontal, smooth bore, 36/1 L/D extruder was equipped a 5 HP drive and 10:1 gear box, four barrel zones, a head zone and die zone, and combination pressure transducer with flush melt temperature indication. The die was a single strand 3.2 mm diameter. A screw with three SFEM II elements was installed, Fig. 1.

The SFEM-II was designed to maximize output while mixing in a flood fed design. The 25mm screw had a channel feed depth of 4.6 mm, a meter depth of 2.3 mm and a P1 clearance of 1 mm. The lengths of the various sections can be judged by the drawing. The SFEM-II can be seen to differ from the SFEM [3] particularly in the pitch of the first melting/mixing element. Another difference is that the first melting/mixing element has a single group (C1, P1, C2, P2, C3) while the first SFEM screw has two groups, Fig. 2. The second melting/mixing element in the SFEM-II is the same as the SFEM first melting/mixing element.

The 25mm conventional screw used as a control was determined by the design that gave the best pressure stability and output. This screw had a channel feed depth of 4.6 mm for 9 L/D, transition for 9 L/D and a meter depth of 1 mm for 18 L/D.

Experiments

Output: The extruder was operated at 120 RPM. Barrel temperatures were set to 238C, 232C, 221C, 221C; adapter and die 221C.

Mixing: An extrusion experiment was performed using a simple blend of materials to investigate the principles of mixing in the SFEM II. To investigate the mixing process, the extruder screw was quickly stopped and frozen in order to produce a solid polymer carcass. The exterior of the carcass shows the progression of mixing at each mixing element. One of the mixers, E2, was examined microscopically to see the interaction between the material blend and SFEM II mixing element. Overall mixing quality was judged using by examining the extrudate.

The extruded rod was smooth and uniform in color. After about 10 minutes of operation the screw was quickly stopped while simultaneously the barrel was cooled to room temperature using forced air. Because of the small size of the extruder, cooling of the barrel proceeds quickly minimizing degradation of the materials and movement of the melt. The high viscosity of the 0.5 MI PP also aids in minimal movement of the melt on the screw while cooling.

After the cooled screw was pushed out of the extruder, pictures were taken of the frozen carcass on the screw, Fig. 3 and then the carcass was removed.

Results

Output: The output rate of the SFEM II was 8.9 kg/hr while the control screw produced 4.2 kg/hour. Respectively, melt temperatures were similar very close at 227C and 228C; drive amps were 9.8 and 6.2; pressures were 76.3 and 82.7 bar, both plus or minus 1.7 bar. It should be noted that the output rate is a higher than expected for the SFEM II [11].

Mixing and Melting: The first screw L/D's are empty, Fig. 3, as these contained unmelted pellets that fell out upon removal. Fig. 4 shows solid bed formation and color development. Generally, the white appearance will mean a poorly melted, very high viscosity material and blue will mean a better developed melt that allows the color to mix. The onset of melt can be observed. There, the C2 channel is just beginning to have melt pumped over P1. About 1 L/D later, C3 is full so this material, too, was sufficiently flowable that it could flow over P2.

In Fig. 5, a fully developed melt, shown by the blue color, fills about half of the channel after the first melting element. Fig. 6 shows material entering the second melting element and color development in the following channels with the result that a surprisingly uniform mixture then enters the third mixer, Fig. 7. Mixing improves during the third mixing element and is uniform thereafter in the metering section.

The microscopic study focused on the material in mixer E2 because high contrast can be seen between the natural and colored material. Fig. 8 shows a thick cross section perpendicular to the screw axis on a lined yellow pad for scale. A detail of mixer E2 can be seen in Fig. 2.

Only one side of the mixer was sectioned, as the other side is a duplicate set of channels. A section was also taken from the extrudate, between the screw and barrel to examine the final mixing (Fig 9) so the picture shows a 25 mm diameter.

Microscopic photographs of the E2 sample were taken and the microscopic pictures were stitched together to provide an overall view (Fig. 10). Of particular interest are the flow lines of contrasting colors, as these give an indication of the movement of the materials.

In order to help in the analysis of the flow lines, a simple 2 dimensional computer flow model was developed using Compuplast's VEL 2D module, Fig. 11, shows the streamlines of the flow model. A readily apparent feature in the model is circulator flows near the top of the channels. Looking closely at the same areas in the sample, Fig. 10, in channels C1 and C2 it is relatively easy to see

the circulatory flows but far less so in C3. Circulatory flows can also be seen at the edges in C1 indicating at that it is partially unmelted, and that condition is not accounted for in the model, nor is there contrasting color available to highlight the flow in the center. It would seem that part of the circulatory aspect of the model can be confirmed. Somewhat surprisingly, the flow model suggests that melt is not only being dragged by the barrel wall from C1 past C2 and into C3, but will also flows back into C2 and C1. This was unexpected, but the close up of the pump area Figs. 12 and 14, seems to show material is flowing backwards into P2. It should be noted that in the model the velocity of the materials flowing backwards is relatively low compared to the velocity at the barrel interface.

Additional information about the circulatory flow can be seen in the residual dye striping remaining on the root of the mixer channels by the dye in the color concentrate, Fig. 13. The angle of the stripes suggests that each channel has a different velocity of rotation and downstream velocity. It can also be clearly seen that the flow lines in the flight following E1 is roughly parallel with the flight while the flow lines in E1 are roughly at a right angle to flight and pumps.

A known mixing mechanism, drag removal of thin film [9], can be readily seen across the top of Fig. 10 as a thin film of uncolored materials.

A 25MM cross section of extrudate from the end of the barrel, which was not occupied by the screw, was section and examined, Fig. 9. At 100 times magnification, there were no flow lines or laminar layering visible.

Discussion

Of mention is the usefulness of doing this work on a 25 mm size extruder. Every aspect of the experiment was easy to perform as compared to larger extruders, and seemingly the results are just as valid. It was even possible to microscopically photograph the entire cross section of the mixer to reveal hidden flow details.

Mixing objectives depends on the mixing task. When mixing a color concentrate into a polymer matrix the primary objective is distribution of the color contained within the concentrate. It is assumed that the colorant is pre-dispersed within the concentrate. The mixing objective would them be fine distribution of the colorant. The degree of distribution is sometimes quantified by the production of laminar layers. Distribution should also occur along the length of the screw, to insure uniformity of the color strength over time.

The three SFEM II elements seem accomplish these tasks of producing laminar layers and distribution over time. Laminar layer production occurs in the dragged film near the barrel, in cross sectional back flows across the three channels, and in the circulatory flows within those channels. Distribution over time occurs as all channels are sourced by material from C1, but then each channel develops different circulation velocities and different downstream velocities. These different velocities are caused by differences in cross channel pressures, channel shapes, and perhaps viscosity within each channel. This should aide in axial distributive mixing.

There is a very evident change in the color development from C1 to C2 and then again from C2 to C3 across the entire cross section. Photographic enhancement of the C1, P1, and part of C2, Fig. 14, allows a first approximation of the elongating flow. For the entire color to change so dramatically from C1 to C2, it would seem that a great deal of C1 flow must be elongated. The dotted lines suggest the flow lines from C1 through P1 and into C2. It is not clear if there are two independent elongating streams or a single long elongating stream.

The entry and exit of P2, Fig. 15, show complex flow streams, apparently elongating in a somewhat similar fashion to those entering and exiting P1. However, the flows seem more complicated and seem to show some flow from C3 into P2 as suggested in the computer model.

It should be remembered that the great improvement in mix quality, above, refers only to E2. Presumably, similar additional improvement occurs again in E3.

Conclusions

Output: The increase in output of 100% over the control is very gratifying. To put that in perspective, in a 25 mm screw processing conventional LDPE with a typical design (4.6 mm feed channel depth, transition, meter 1.5 mm channel depth with the lengths equally divided and at the same rpm) the screw will produce about 8.1 kg/hr whereas the SFEM achieved 8.9 kg/hr *despite a 10% lower density*. Therefore, PP may be economically substituted for interchangeable olefin applications.

Mixing: It should be noted that when a 0.5% color concentrate is added to a 25mm extruder with conventional or barrier screws, the color variation of the strand varies distinctly by eye. This did not occur and the absence of stria in the 1 inch diameter cross section is extremely encouraging.

The SFEM has proven to be effective in many mixing tasks but the exact mechanisms for its success are not perfectly clear. This test and analysis shows that some commonly known extrusion mechanisms interact with the unique geometry of the SFEM II to provide superior mixing results. Complex elongational flows can be seen. It should be noted that this analysis is only for E2. These flows combine and spirally mix in flights after E2 before entering E3, where presumably, similar mixing mechanisms occur to enhance the mixture.

Additional studies with higher contrast materials are anticipated and it is hoped that additional modeling will shed light on the mixing mechanisms for even more effective SFEM designs in the future.

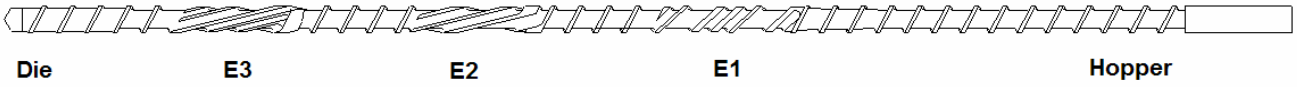
It is now established that a low resistance screw can increase the output of PP in a very substantial way. This same principle is of value for many materials. One, RPVC powder—a material historically unrocessable in the SSE, has also been shown, not only that it can be processed but at 180 rpm—whereas the typical screw speed is 30 rpm. [10] It seems likely, then, that the SFEM II design is also applicable to similar materials where low friction marginalizes the application. Candidate resins include members of the fluorocarbon family, high molecular weight materials, additives and many fillers.

In brief, the low resistance SFEM II [11] screw will notably expand the range of the SSE and increase output of marginal materials. This offers significant profit potential.

References

1. K. Luker, *"Summary Results Of A Novel Single Screw Compounder,"* Antec 2007.
2. K. Luker, *"New Thin Film Single Screw Venting Mechanism Tested On Wood Flour/Pellets, 35% Calcium Carbonate/PP Pellets and Undried PMMA,"* Tappi 07.
3. K. Luker, *"Novel Elongational Mixer for Thermally Sensitive Materials,"* Antec 2008.
4. K. Luker, J. Lynch, T. Nosker, *"A Novel Micro-batch Mixer That Scales To A Single Screw Extruder,"* Antec 2008.
5. D. Lorenc, K. Luker, *"Novel Single Screw For RPVC Powder That Compounds,"* Antec 2009.
6. E. Stangland, J. Dooley, M. Spalding, et al, *"Fundamental Characterization of Polypropylene Extrusion,"* Antec, 2002.
7. C. Rauwendaal, P.Gramann, *"Back-Mixing in Screw Extruders"*, Antec 2000.
8. Z. Tadmor, I. Klein, *Engineering Principles of Plasticating Extrusion*, Kriefer Publishing, Chapters 6, 7.
9. D. Lorenc, K. Luker, *"Novel Single Screw For RPVC Powder That Compounds,"* Antec 2009.
10. http://www.extrusiontechnicalservices.com/site_info.php
11. K. Luker, U.S. Patent 6,962,431 B1 (2005)

Figure 1. Screw with three SFEM elements, E1, E2, and E3.



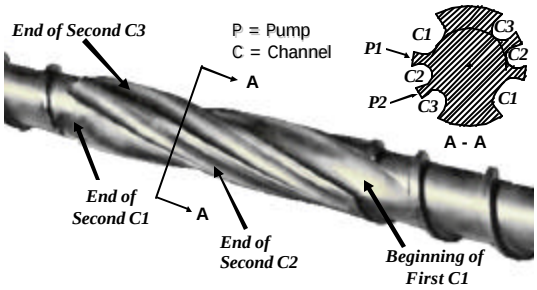
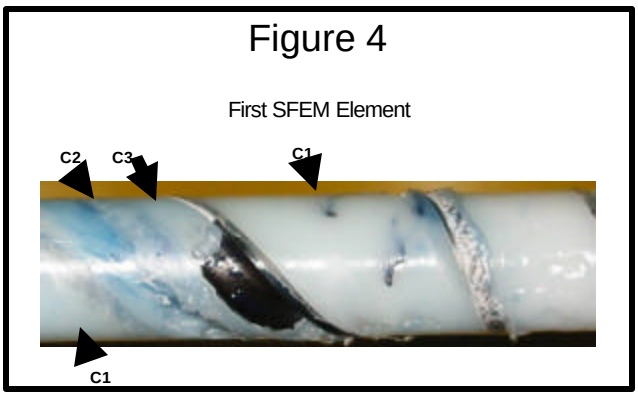


Figure 2: Nomenclature and E2 design

Figure 3. *The screw with frozen carcass.*



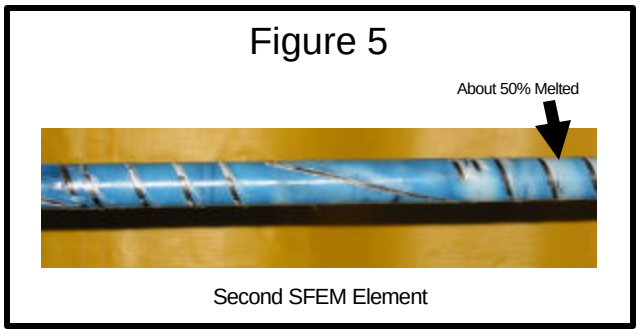


Figure 6 Material leaving the E2k left, is surprisingly uniform

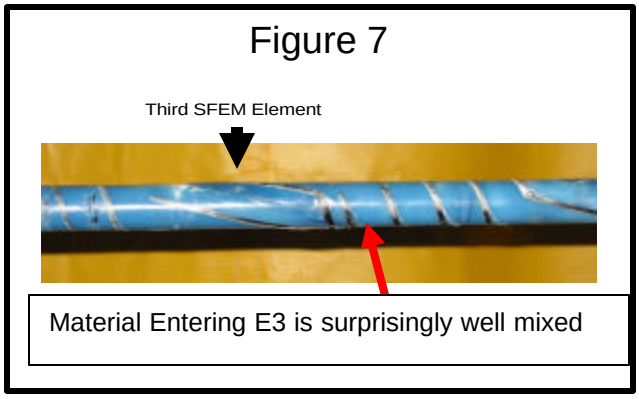


Figure 8: Thick Cross Section of E2

Fig. 9: One inch Cross Section of Extrudate Between Screw and Breaker Plate

Fig. 10: Stitched Photos of E2

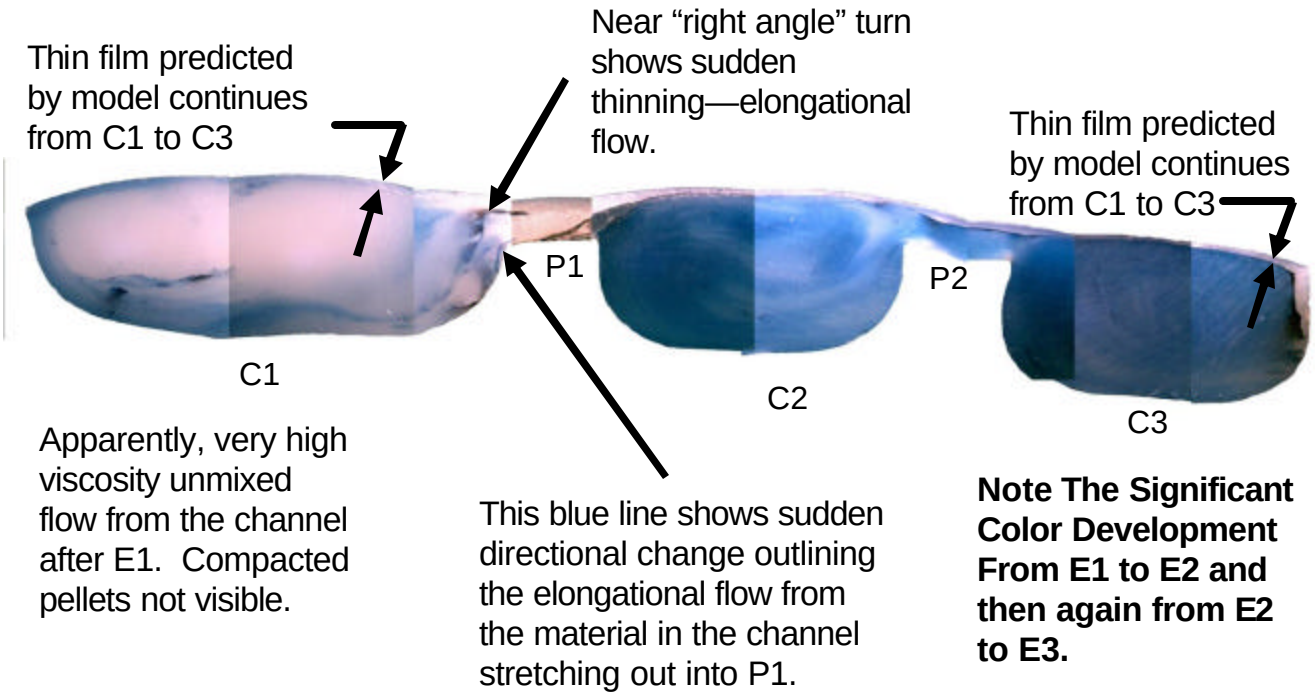


Fig. 11: E2 Mixer 2D Flow Model

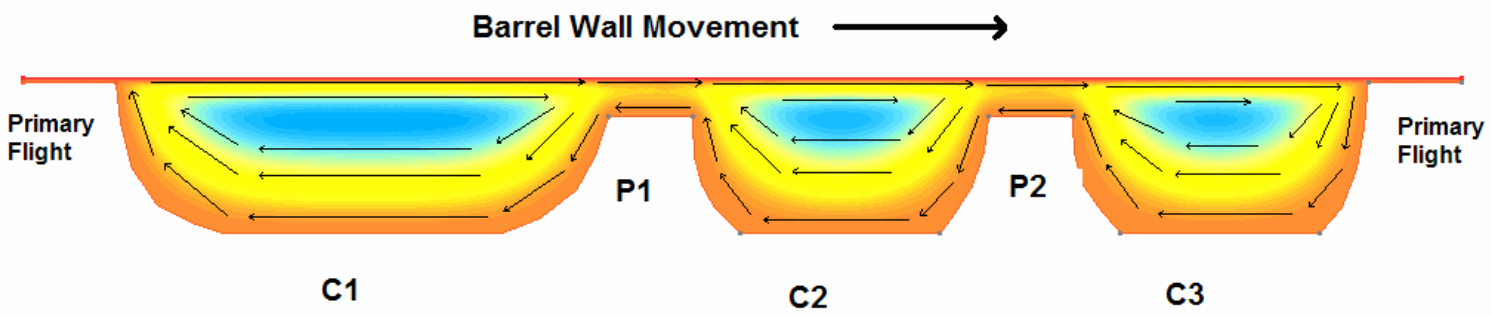


Figure 12. Pump areas between C2 and C3 showing back flow

Figure 13. Circulation pattern left on mixer root of E2

Fig. 14 Computer Enhanced Picture Of Flow Lines
Dotted Green "Best Guess" for Elongating Flows C1 to C2

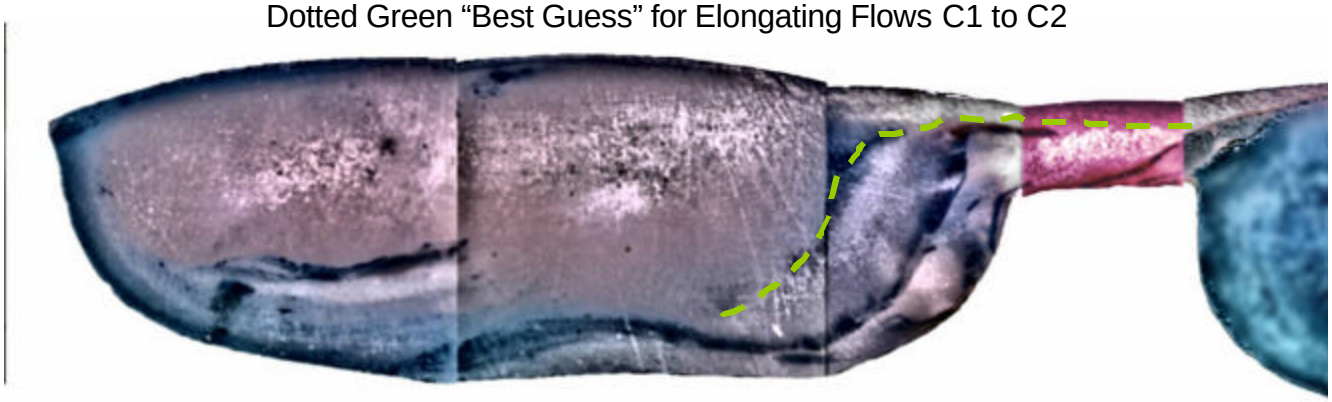
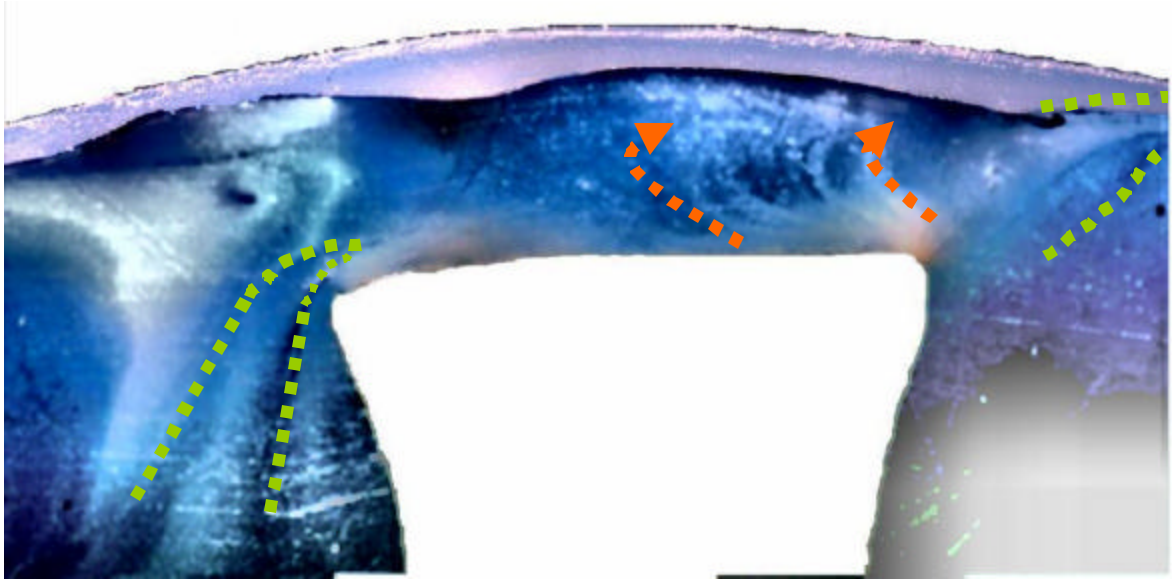


Fig. 15: Enhanced Entry and Exit Of P2 Elongating Flow Lines: Green
Back Flow: Orange



Key Words: elongation, polypropylene, mixing, SFEM, Elongator, compounding