

THE DEVELOPMENT OF A NEW ELONGATION MIXING SCREW FOR FOAM AND ITS ADVANTAGES FOR FOAMING PLASTICS

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Abstract

Single screw extruders (SSE) are known to make high density foams in a single extruder process. The process is complex. The materials (the polymer and blowing agent) must be well melted, and mixed, kept cool, kept continually under pressure and processed at a high output rate. The materials themselves must be selected for melt strength properties and carefully matched to the blowing and nucleating agent system.

This paper will describe a new screw that is uniquely helpful for foaming. It includes a new screw innovation—the low resistance screw—and the incorporation of multiple elongational flows for mixing. This paper will also describe proper material selection, processing guidelines related to this screw design, and how the combination of these technologies help to provide advantages when processing foamed plastics.

Introduction

The genesis of this screw began with an elongational mixing screw where the mixing quality was shown equal to a twin screw for melted mixtures Fig.1 and extremely effective for particulate blending [1]. Since the SSE has suffered from a lack of mixing for many years, these innovations, in theory, could be very useful in making foams.

However, these Recirculator (hereafter AFEM for axial fluted elongational mixer) and Elongator (hereafter SFEM for spiral fluted elongational mixers) mixing screws were originally starve fed. Starve feeding would, unfortunately, allow the blowing agent gas to escape through the hopper and reduce or eliminate the foaming.

A flood fed design was recently developed, hereafter SFEM II, showing that elongational flows that produce quality mixing could be preserved such that no striation lines could be observed at 100X magnification [2]. The screw also proved to have an unusually high output at three times that of a conventional screw for a 0.5 melt flow polypropylene (PP) [3].

A new polypropylene with high melt strength, a compatible foaming agent and nucleating agent was used with the SFEM II screw. This combination of materials and screw design produced a foamed polypropylene sheet during the 2009 NPE [4] with good results. Densities achieved were approximately .5-.6 without optimization.

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, was 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 [5]. The circulating flow in the screw channel causes a wide variation in the amount of mixing experienced by the polymer [6]. 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 [7, 9]. Since the SFEM has twin like compounding in many applications [1, 8, 9], an initial study of the quality of mixing PP foam was of great interest especially since this was not known.

Materials

The foam sheet was composed of Japan Polypropylene Corporation's NEWFOAMER™ FB5100 which is a high melt strength PP grade and 1.25% of Reedy's SAFOAM® FPE-50 foaming agent. The materials were blended by hand shaking in a bag prior to extrusion and added to the extruder hopper (flood feeding). These 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 a combination pressure transducer with flush melt temperature indication. The die was a flexible lip 6 inch die with a 1 mm maximum gap and equipped with a zero length land. A low resistance screw with three SFEM elements was used, Fig. 2, 3.

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 its predecessors 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 earlier SFEM screws had two groups, Fig. 3.

Experiments

Output: The extruder was operated at 60 RPM. Barrel temperatures were set to zone 1, 195C, zone 2, 200C, zone 3 and 4, 205C, adapter 200C and die 195C.

Results

Output: The output rate of the SFEM was 4.4 kg/hour. Melt temperature was 205C.; drive amps were 8.2, pressure was 44 bar. It should be noted that the output rate is a higher than expected for the SFEM [10].

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 scalable.

Mixing objectives depends on the mixing task. When mixing a foam into a polymer matrix, the primary objective is distribution of the foaming agent and nucleating agent contained within the concentrate. In foam, drop melt, proper mixing and temperature is essential to insure that the viscosity of the polymer has the right consistency to capture the bubbles. The CO₂ acts as a nucleant and foaming agent and creates a microcellular structure with a smooth solid skin around a fine cellular core. Particle size, distribution purity, and a controlled gas release are tailored to provide many, very small nucleation sites that create this fine and uniform microcellular structure (Reedy [11]). When CO₂ changes phase from a supercritical fluid to a gaseous bubble due to the pressure drop, heat is absorbed. The changes in phase results in an endothermic process of heat absorption. The saturated CO₂ exerts an internal pressure in the product that results in improved material flow characteristics which enables the processor to feed polymeric material very consistently. Since the product is still saturated with CO₂ and is significantly plasticized, lower processing stresses are evident in the product. The material has more time for the molecular chains to relax and for the stresses to dissipate. Eventually, the gas will permeate through the polymer and escape to the atmosphere. The mixing objective would then be fine distribution of these ingredients so that each bubble that forms is of similar size. We believe that the size of the liquid droplets and the amount dispersed in the polymer matrix has a

lubricating effect. This reduces shear heat and improves melt flow and the polymer melt index. The rate of bubble growth is related to gas solubility, melt temperature, and the pressure drops over time. Fine particles that produce liquid droplets tend to produce fine emulsions and bubbles will take more time to produce. 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.

This type of distribution of the foaming agent and nucleating agent is key to achieving consistent foaming. Much research has been done that shows surface energy differences in nucleation. The gas molecules will have a tendency to congregate at the weakest point, known as the nucleation site. Improving the mixing of the liquid gas and polymer, like the extrusion system that is being shown in this paper, will improve the emulsion chemistry in typical equipment.

In addition to proper mixing of the system, pressure is also a key factor. The pressure release rate directly affects the rate at which foaming occurs. The gas bubbles exert a higher pressure and therefore a higher release rate. This high pressure is crucial to foaming along with maximum extrusion rates in order to prevent pre-foaming. As the resin laminar flows from the barrel into the die, molecules stick to the side of the die. As the die land is extended, there is more laminar flow, resulting in lower die exit pressure. Basically, the less pressure exerted will equate to a lower pressure release rate which results in much less foaming (Reedy [12]).

The three SFEM II elements seem to 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 aid in axial distributive mixing.

Since it is very difficult to capture pictures of micro-bubbles in a cooling experiment, colorant can be used to simulate the mixing of foaming agent and nucleant package. In a study of PP and color, a computer model of the E2 Flow was developed, Fig. 4. 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. 5, 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. 6, 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.

Conclusions

Output: The high output of PP in this study is very gratifying. To put that in perspective, at 60 rpm 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 2.1 kg/hr whereas the SFEM achieved 4.5 kg/hr *despite PP's 10% lower density*. Therefore, PP foamed products may be economically substituted for interchangeable olefin applications.

Mixing: It should be noted that the bubbles in the study, Fig. 7 seem small and uniform indicative of good mixing.

In another study [2], the color concentrate was added at only 0.5%. At this low level, conventional or barrier screws show pronounced color variations that are easily distinguished by eye. This did not occur and the absence of stria at 100X in the 1 inch diameter cross section [2] 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. Some commonly known extrusion mechanisms (shear) interact with the unique geometry of the SFEM II to provide superior mixing results from elongation and these complex elongational flows can be seen. It should be noted that the color analysis is only for the E2 mixer. The E2 flows combine and spirally mix in flights after E2 before entering E3, where presumably, similar mixing mechanisms occur to enhance the mixture once again.

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 material, rigid polyvinylchloride (RPVC) powder—is historically unprocessable in the SSE. Not only has the SFEM II also been shown to process RPVC powder [12]

only that it can be processed but at 180 rpm—whereas the typical screw speed is 30 rpm [12]. This is of particular interest because a foamed RPVC made from powder has substantial material savings.

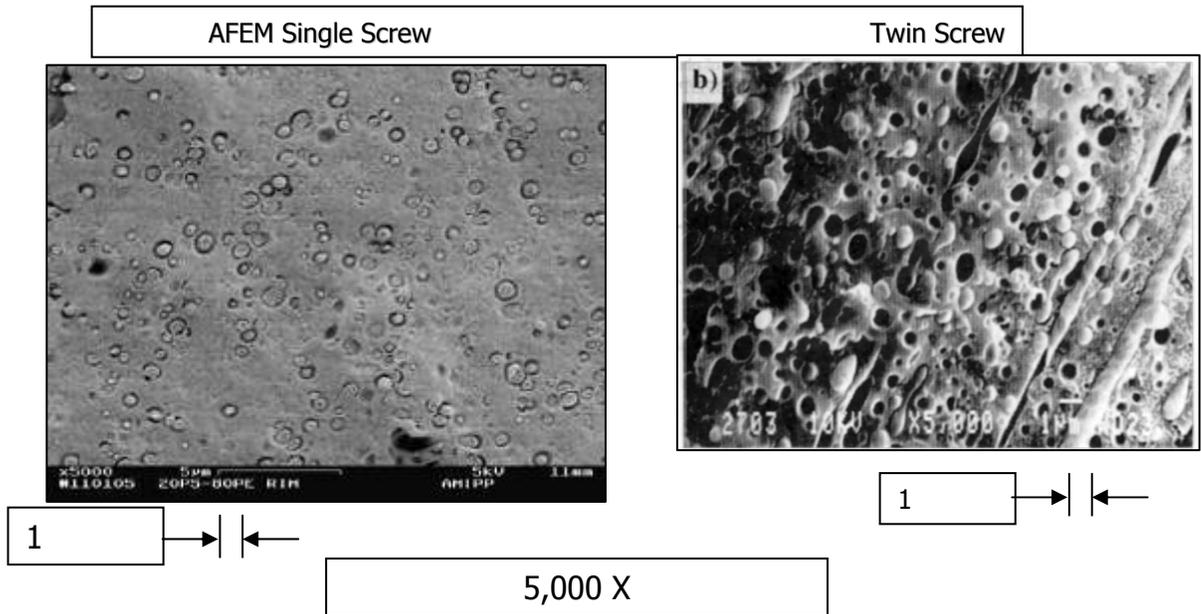
It seems likely, then, that the SFEM II design is also applicable to similar materials where low friction marginalizes the application. Candidate resins include members of the fluorocarbon family, high molecular weight materials, additives and many fillers.

In brief, the low resistance SFEM II [13] screw will notably expand the range of the SSE and increase output of marginal materials. By combining this system with foam, it offers significant profit potential. There are many types of foam systems. Reedy is now offering a CO₂ pumping system for those companies that would like to pump the gas in or you can use a standard blowing agent and/or nucleating agent. The end result will allow you higher extrusion outputs, improved insulation properties, increased part rigidity, lower densities, decreased cell size with improved uniformity, and overall cost savings. In today's economy, saving cost is the way to go. You too can achieve it with the right combination of equipment and material selection.

References

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Fig. 1: Comparison of Co-Continuous Domains: 20PS/80PE



Left picture courtesy Rutgers. Right picture, Antec 95, “CO-CONTINUITY AND PHASE INVERSION IN HDPE/PS BLENDS: THE ROLE OF INTERFACIAL MODIFICATION” by Daniel Bourry and Basis D. Favis

Figure 2: Screw with three SFEM elements, E1, E2, and E3.

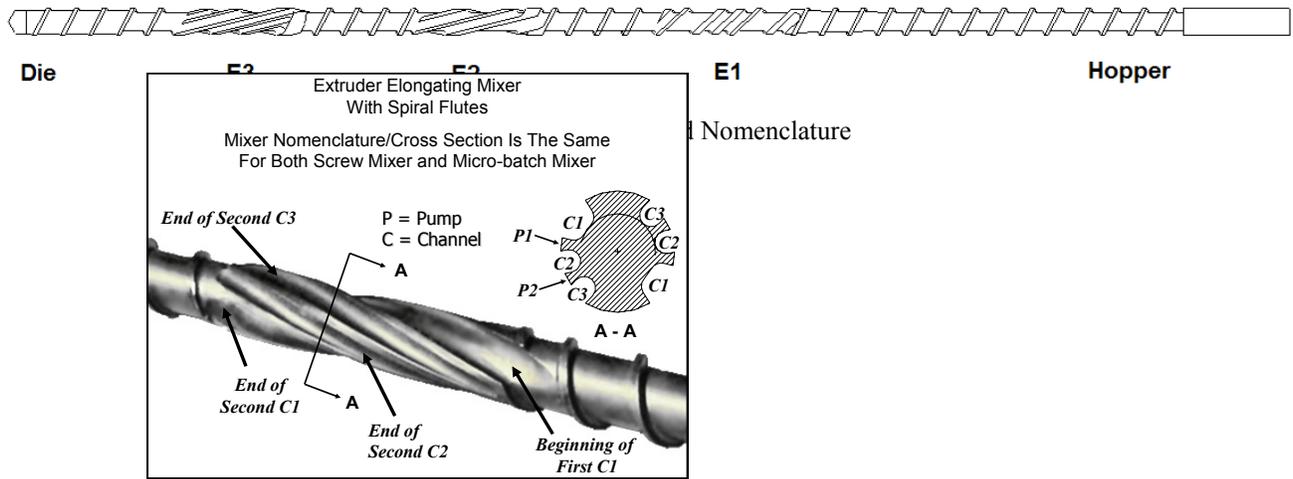


Fig. 4: Computer Model of E2 Flow

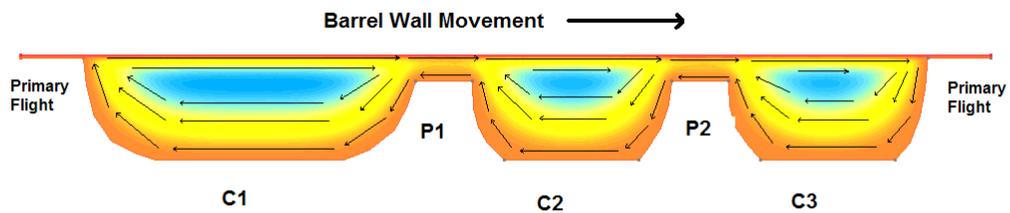


Fig. 4: Nine Stitched Photos of E2

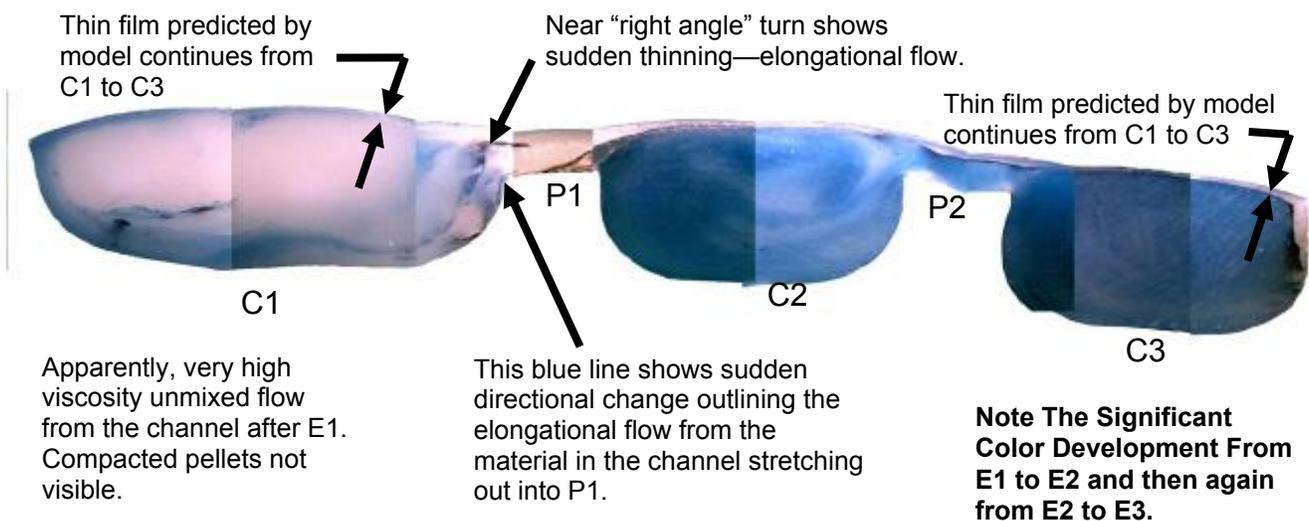


Fig. 5 Computer Enhanced Picture Of Flow Lines
Dotted Green "Best Guess" for Elongating Flows C1 to C2

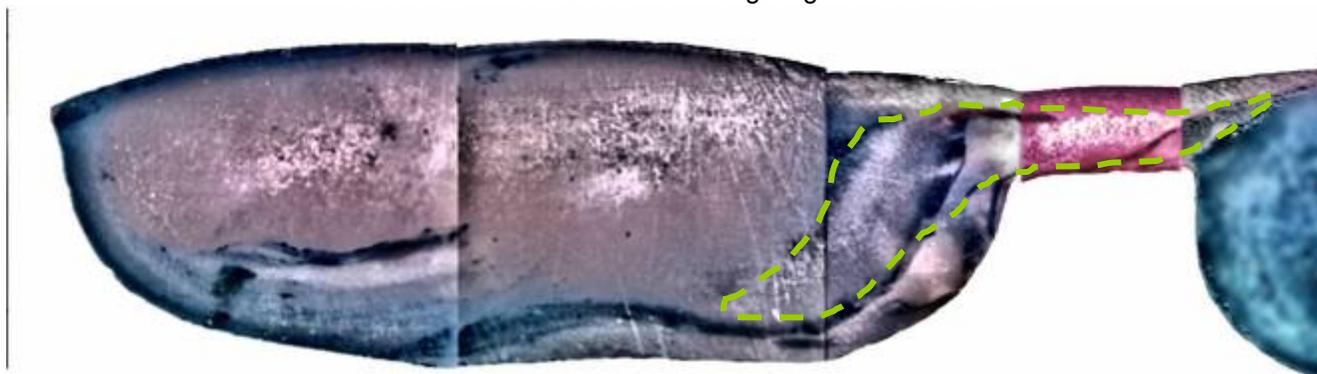


Fig. 6: Computer Enhanced Entry and Exit Of P2 Elongating Flow Lines:
Green: Elongating Flows
Back Flow: Orange

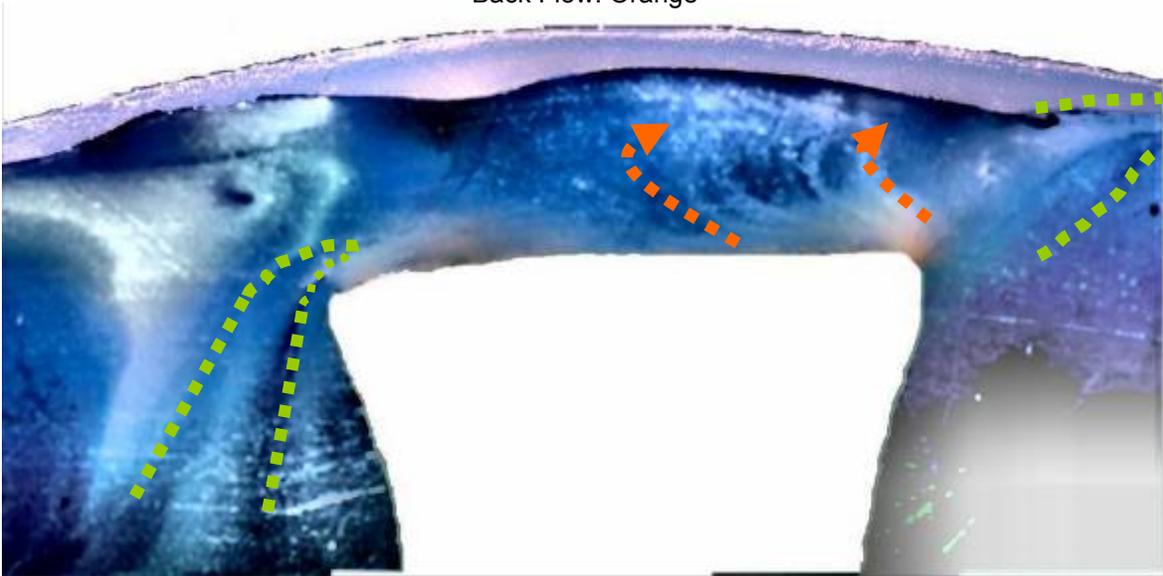


Figure 7: Polypropylene Foam Bubbles In Sheet

