3 Dimensional Mixing
An Orderly Mixer For Single Screw Compounding

Abstract: Historically, single screw extruders (SSE) have been poor mixers using shear, melt separation and recombination. Meanwhile, twins have used chaotic elongation for mixing which made them far superior for both distribution and dispersion to the SSE.

Single screw mixing can now be both elongationally dominant and orderly. The combination can yield results that are superior to twin screws for distributive mixing. Distributive mixing is now known to be eight times better than twin screw mixing of an immiscible polymer blend in work by Dow Chemical. Particulate of CNTs shows superb distribution even at the 200nm level Polymer blending and particulate mixing are among the most sought after forms of mixing.

The principles discussed in this paper examine the 3D mixing flows that are now used for many mixtures previously impossible for single screws. For example, 40% flame with pellets made directly into 4 mil film, pearlescent compounding of mica with pellets, clay and pellets and 20% magnetic material with ABS pellets compounded directly into 3D printing filament and mixing of active pharmaceuticals for HME applications.

Many compounding applications require the degassing of volatiles. The traditional SSE two-stage screw, owing to the thick melt pool, is a poor degasser. The 3D mixers discussed here create a thin film making them excellent degassers. Three vents are possible in a 36/1 L/D SSE; each mixer can have venting capability.

Melting by elongation, rather than shear, lessens temperature rise, promotes increasingly stable pressure and increases output.

The 3D mixing technology increases mixing performance while maintaining the natural advantages of the single screw: High, stable pressures at low cost. Replacement screws are now available for all brands and sizes. Output is not reduced using this technology. For some materials, it is known to improve.

History

For more than a century, single screw extruders (SSE) were well-known as poor mixers compared to twin screws—the most popular being the intermeshing co-rotating twin screw (CRTS). Mixing can be thought of as dispersive i.e. to break into smaller units or distributive i.e. to order in space. The SSE was considered vastly inferior for both distributive and dispersive mixing.

In the late 1900's it was discovered that one of the primary reason for the CRTS's success was melt elongation at the intermesh region. There, some of the melt is pulled between the two screws just as a rubber band can be readily pulled at each end. Elongation is the primary distributive melt mixing mechanism. Since the SSE only has one screw, it seemed obvious to the casual observer that it could not stretch melted material just as it seems obvious that you cannot stretch a rubber band when you can only grab one end.

The most obvious way to modify the SSE for elongation was to use the barrel in some fashion to to anchor the melt material so that the screw could then employ a stretching force. These modifications did not surpass the CRTS in quality. They did however add significantly to the cost of the SSE and were not flexible.

In the 21st century, a patent was issued to Randcastle for an elongational mixing screw. It is now a production tool capable of better distributive mixing than the CRTS. It does this because it is capable of stretching all of the melt material multiple times in all three dimensions in and orderly manner. It does this without barrel modification, loss of output or increased temperature.

Introduction

Disorder is the disruption of regular arrangement. It is chaos. It is non-uniformity.

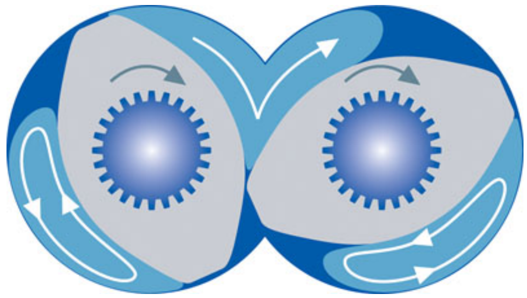
Order is the arrangement according to a particular sequence, pattern and method. It is uniformity. The quality of distributive mixing is best described by its orderliness. Processing tools that are orderly can make an ordered mix. Processing tools that are chaotic will make a less orderly mix as chaos introduces disorder.

It is well-known that twin screws are not perfect distributive mixers and it's helpful to understand why. Elongation in the CRTS only occurs at the intermesh. Most of the material is not in the stretching intermesh. Instead, it is in the channels. There, it is transported by drag flow that does not contribute much to orderly mixing.

The intermesh stretching percentage can be increased by limiting the feed rate so that there is less material in the channels. This lowers output and production and so is not considered generally viable.

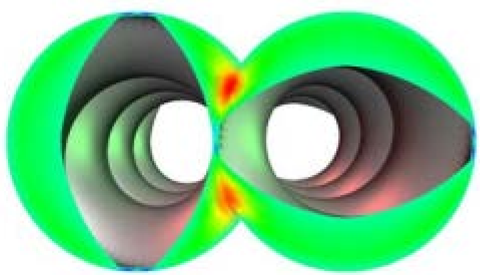
Once material is melted, it moves through the CRTS channels taking a figure eight path arriving at a first intermesh. There, some percentage of the total is stretched and sheared. Material moves to the next intermesh, a percentage is again stretched and sheared. The process repeats. It is important to note that within the intermesh, not all of the material is stretched; not all of the material is sheared. Not all of the material is not treated in the same way. It is not orderly. During the progression from intermesh to intermesh, some material will be stretched mixed many times. Some material never.

To improve mixing within the CRTS, various mixers are added. Perhaps most common are bilobal kneading discs:



Above, two thirds of the material is completely isolated from the intermesh region where elongation can take place. Further, when observing the material near the intermesh region, about half is being pushed away from the intermesh region. "Pushing" is the opposite of "pulling" or elongation. Of the remaining half, a significant amount is being pushed into the intermesh region.

This is shown graphically[1] below where the intensity of mixing in the small intermesh region is displayed using different colors. Different colors indicate the disorder at the intermesh.



While mixing is well-known to improve with such mixers, such mixer cannot impose order. Using this type of mixer introduces disorder and chaos which limits ordering—i.e. limiting distributive mixing. There are many other twin screw mixer types besides lobal mixers and some are designed to promote distributive mixing. None are known to impose orderly mixing.

Advancement in SSE design now has advantages over the CRTS for distributive mixing. Put simply, 100 percent of the flow through the screw will experience elongation and shear on multiple occasions in an orderly, low intensity fashion three dimensionally. Because the mixing is orderly, it produces an orderly, uniform mix.

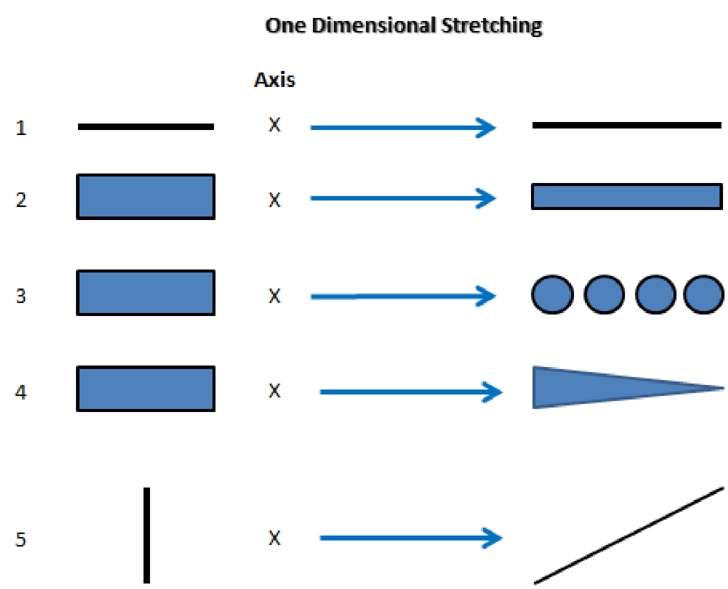
Uniform mixing is inherently better than chaotic mixing. It is now known that orderly mixing can produce results that are significantly better than the CRTS.

[1] Dispersion of Nanoparticles Using Twin Screw Extrusion Technologies; Challenges and Opportunities Dilhan Kalyon/Seher Ozkan/Halil Gevgilili/ Jim Kowalczyk* Stevens Institute of Technology * Material Processing & Research Inc. http://www.pica.army.mil/jocg/files/2006/15%20-%20Dispersion%20of%20Nanoparticles%20Using%20Twin%20Screw%20Extrusion%20Technologies,%20Challenges%20and%20Opportunities.pdf

Principles of 3 Dimensional Mixing

We usually conceive of real objects have three dimensions. Mixing is best advanced towards uniformity by stretching and folding. Orderly mixing requires an understanding of what is being stretched and the order of stretching. Mixing in all three dimensions is required in order to get effective, distributive mixing. Mixing in all three dimensions is not linear but exponential (to the cube) so it is vastly better than mixing in one (linear) direction .

One Dimensional Stretching: Below, (1) a line segment has one dimension. If it were stretched into a longer line segment, the stretching is one dimensional. There are many possible flows that may be stretched in one direction. A molten strand (2) may be envisioned surrounding an axis and stretched. A molten strand might break up into droplets (3) but it's still one dimensional mixing. If a molten rectangle were held at one end (4) on the left and stretched in one direction it would become a triangular. Shear (5) in an extruder is one dimensional. One point adheres to the screw and the other to the barrel.



Many single screw extruder mixers are just one dimensional mixers. UC (Maddock), UC spiral (Egan) mixers rely almost entirely on shear mixing. Sometimes, there is a first a UC and then a UC spiral mixer. Such mixing is then first one dimensional and then one dimensional a second time.

All the barrier screws (with large or small clearances) mix one dimensionally in shear over the barrier. Often, barrier screws are paired with UC or UC spiral. When paired, mixing is still one dimensional shear over the barrier and then one dimensional shear in the mixer.

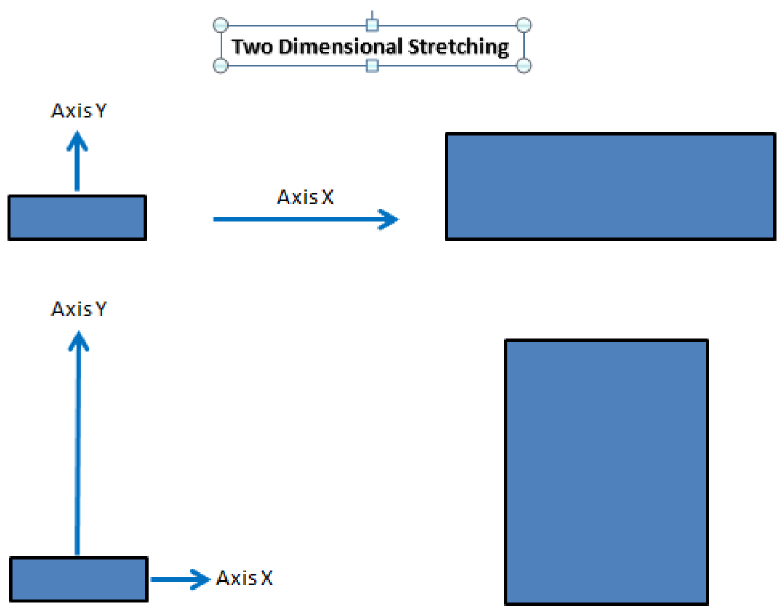
Some mixers shear repeatedly by passing some material over an intermediate flight. At least some material moves from one channel to another shearing in one dimension though not in an equal fashion. A mixer like this is the double wave screw.

One mixer claims to create droplets (3) through stretching pins. Whatever mixing occurs is simple, one dimensional, stretching. Mixing is unequal since material will move around a pin. Some material will mix less and some more for unequal mixing.

It is important to note that the shearing type mixers described are resistive to flow. Material must be pushed over the barrier. To overcome the resistance of the barriers to flow requires pressure flow. Pressure flow (as in flow through a pipe) is not the intention of a shearing type mixer. Whether UC or barrier, the intention is drag flow and shear. Pressure overcomes simple shear making for a combined flow of drag and pressure flow which then inhibits what simple shear might accomplish for mixing.

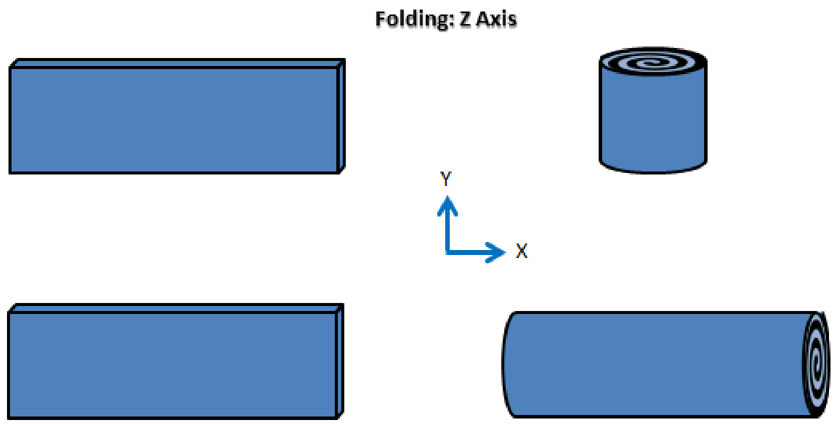
It is also important to note that overcoming barrier resistance by pressure raises the temperature of the melt.

Two Dimensional Stretching: Rectangles and cylinders, represented below, have two dimensions and maybe stretched in both directions. Here, unequal stretching is show in both directions.



There are two single screw mixers that are known to stretch significantly in two dimensions—Randcastle's Recirculator and Randcastle's 3D Elongator. Further, all the flow can be processed through their two dimensional stretching fields.

Folding: Material may be rolled or folded about an axis. A flattened plane may be, for example, blue on one side and black on the other. When rolled about an axis, it will have a spiral pattern of blue and black as below.



In such a case, the thinner the rolled blue and black material, the finer the spiral distribution will be.

Some mixers are known to roll material coarsely as above such as the UC and UC spiral mixers. The coarse layers are a function of the gap in the shear region which is usually not less than 0.04 inches.

The Randcastle 3D Elongator is known to produce a layer that is about 0.002 inches thick or 20 times finer than coarse mixers. This is because it drawn in a free state without little or no resistance before it is rolled in the final channel.

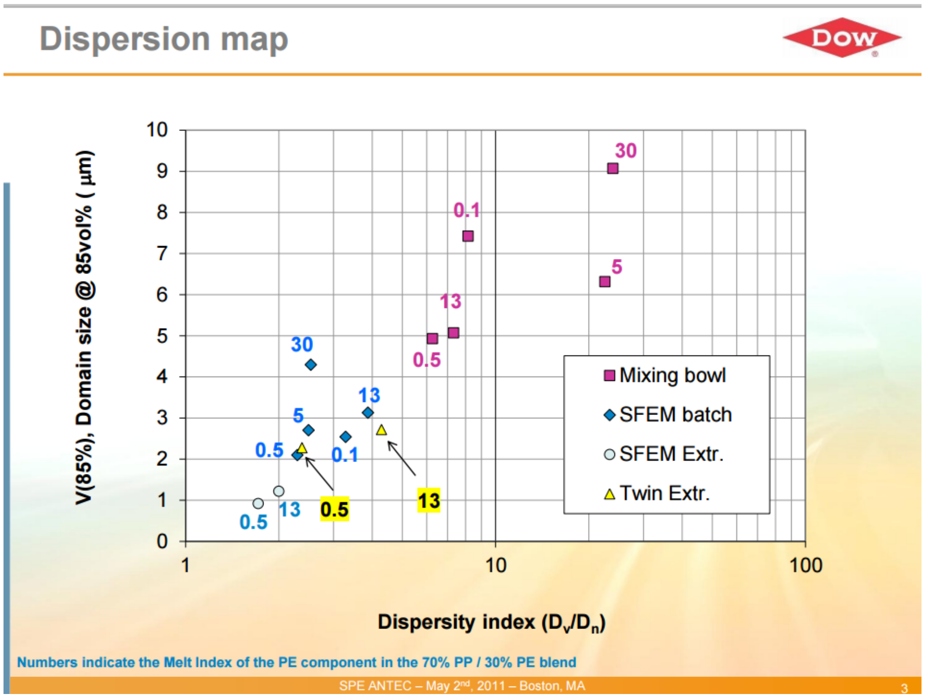
Examples of Surprising Mixing With An Orderly SSE Mixer

Broadly, there are two common types of distributive mixing: Polymer mixing and particulate mixing.

Polymer Mixing: Dow Chemical presented their research[2] on polymer mixing of a TPO at Antec 2011. Previously, it was thought that making a good TPO was impossible for a SSE. That is no longer true. The graph below shows that the orderly Randcastle SFEM mixers (SFEM is the generic name for the Randcastle 3D Elongator standing for Spirally Fluted Elongational Mixer. A

[2] FACILE TPO DISPERSION USING EXTENSIONAL MIXING Stéphane Costeux, Mark Barger, Keith Luker*, Anand Badami, Kim Walton The Dow Chemical Company, Midland, MI (U.S.A.) *Randcastle Extrusion Systems, Inc., Cedar Grove, NJ (U.S.A.) Antec, 2011

flute is also called a channel; we use the terms interchangeably) were 8 times better than the Dow CRTS.

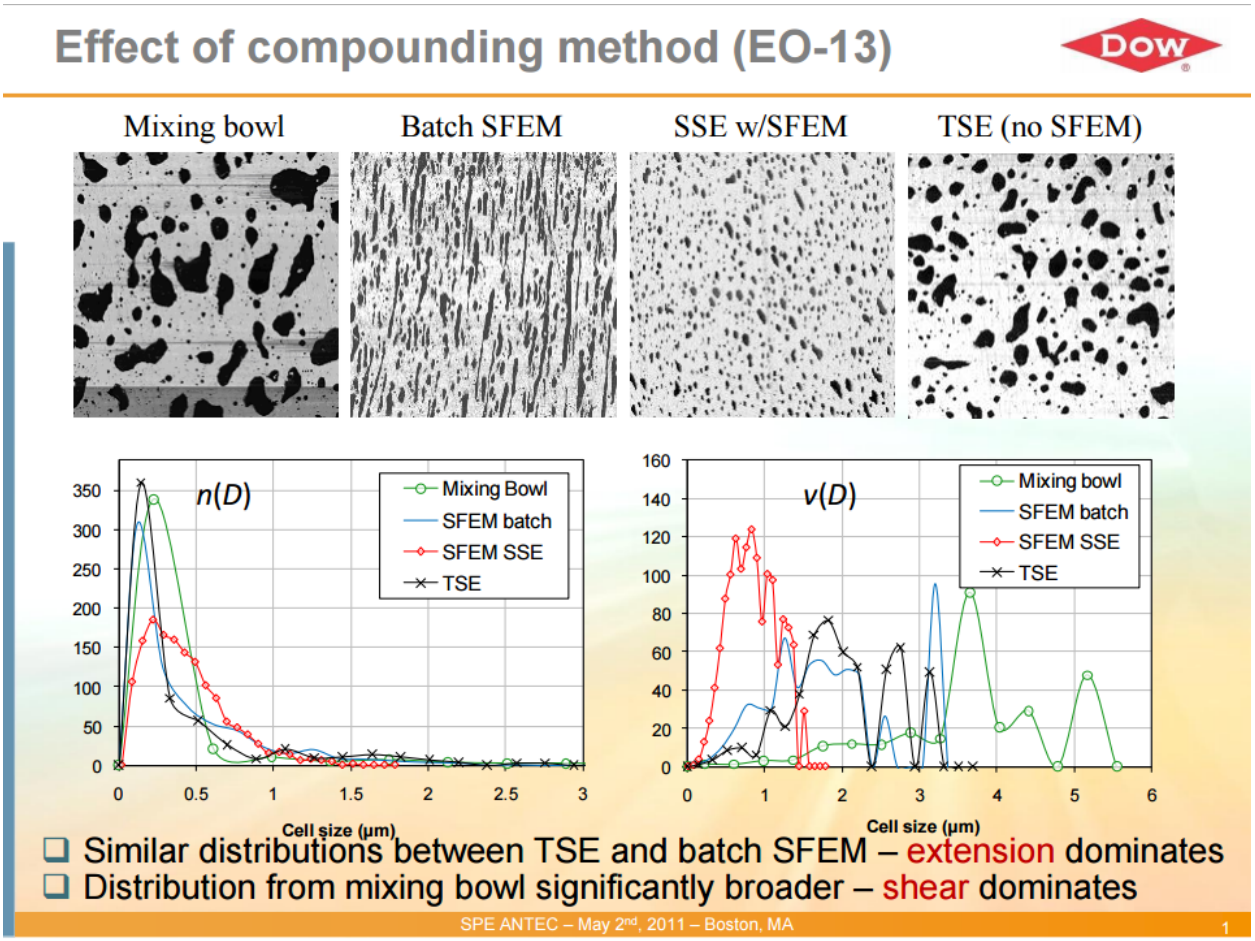


Above, the domains of the orderly SFEM Randcastle Elongator were half the diameter of the disorderly CRTS. The volume of a sphere (an average domain) is reduced by eight times when the diameter is halved. So, it would take 8 of the 1 micron Randcastle domains to equal one of the 2 micron domains of the CRTS. Quantitatively, using domain size as a measure of mixing quality, *the SFEM mixed 8 times better than the CRTS.*

In terms of dispersity, the orderly SFEM mixer is also significantly better than the twin, note that dispersity is on the log scale, so at least 50% better.

The graph also shows a well-known staple of mixing—the mixing bowl (a kind of batch mixer rather than continuous mixer such as an extruder). It is comparable to Randcastle's SFEM batch mixer. The SFEM batch mixer uses a very similar technology to its screw technology. Using domain volume as a measure of mixing quality, the mixing of the SFEM batch mixer is 10 times better than that mixing bowl. This quality was achieved in 3 minutes for the Randcastle SFEM batch mixer compared with 10 minutes for the mixing bowl.

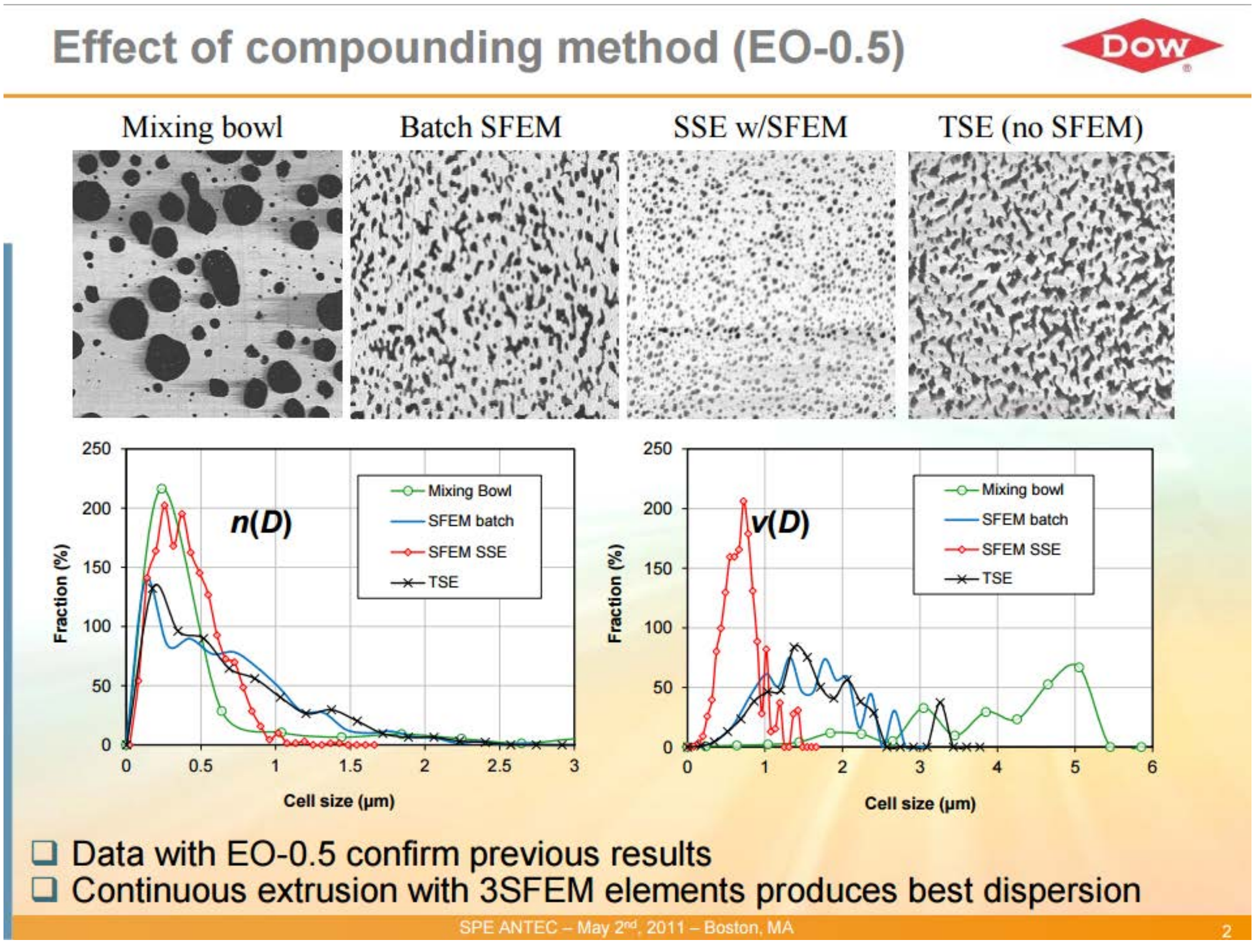
The Dow presentation included pictures and histograms (the 13 in EO-13 represents the melt index of the PE component in the 70% PP 30% PE blend):



The AFM (atomic force microscopy) pictures are striking.

When observing the domains of the SFEM batch mixer in the picture above, it is important to remember that the mixer was only run for 3 minutes rather than 10 minutes for the mixing bowl. The SFEM batch mixer picture shows very elongated domains. While speculative, it seems likely that had the SFEM batch mixer processed for 10 minutes like the mixing bowl, that the elongated domains would have continued to stretch to their breaking point and become smaller.

Below are the pictures and histograms for the 0.5 MI (the 0.5 in the EO-0.5 represents the melt index of the PE component in the 70% PP 30% PE blend):



Again, the AFM pictures are striking. The histograms quantify the mixing for comparison.

Particulate Mixing: Historically, SSE mixers were compared to other single screw mixers rather than to the CRTS. Typically a heavily pigmented light material was made and then let down with carbon black particulate in color concentrate to make a rod. The rod was then examined by eye for black stria. The SSE mixer with the most diffuse stria was judged the best mixer.

Randcastle presented data[3] using this method at Antec. The rod made by the Randcastle SFEM three mixer screw (also used in the polymer mixing study above) was so fine that it showed no stria of black even at 125 times magnification.

Another method of studying particulate mixing is to mix very small materials into polymers and then examine the materials at high magnification. For example, Randcastle presented data at Antec[4], showing 30 to 60nm ceramic balls well distributed at the 500nm scale.

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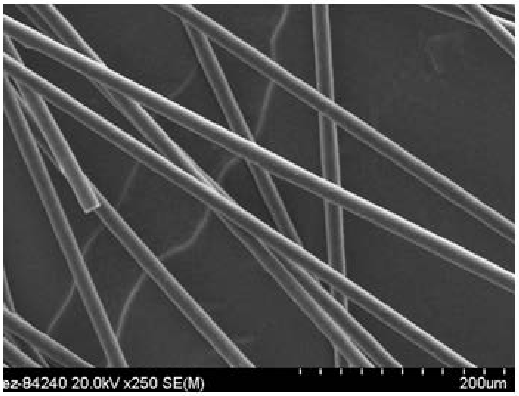
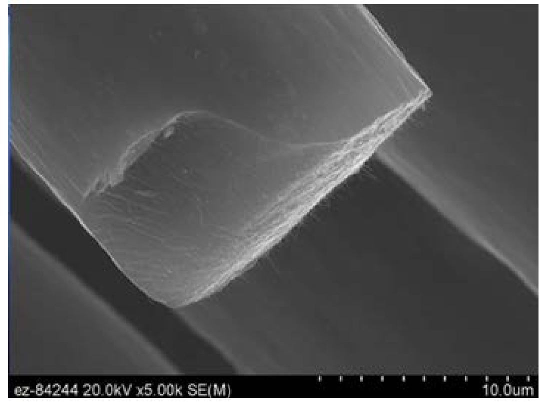
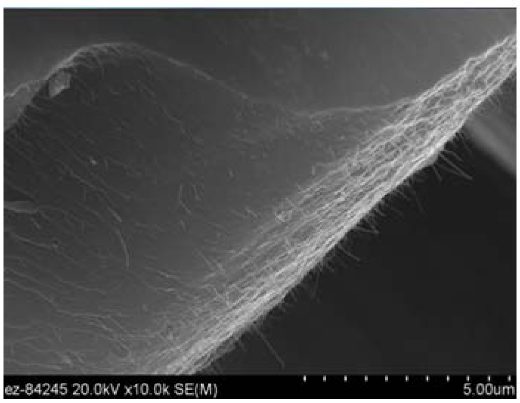
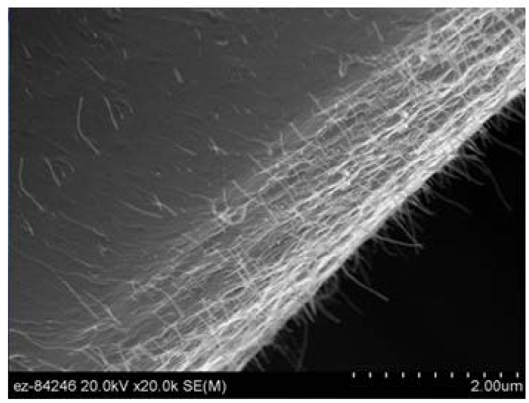
[3] COMPARISION OF FLOW STRIATIONS OF VARIOUS SSE MIXERS TO THE RECIRCULATOR AND ELONGATOR MIXERS Keith Luker, Randcastle Extrusion Systems, Inc., Cedar Grove, NJ Antec 2010

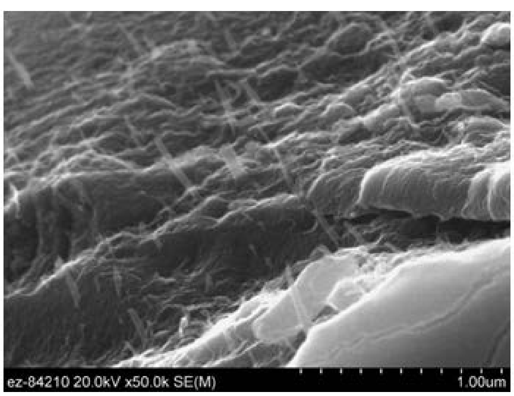
One Randcastle customer worked with carbon nano tubes (CNT) making lignin fibers. The pictures are particularly interesting *when we consider orderliness of CNT distribution* looking in particular for agglomerations of CNTs and at the distances between CNTs:

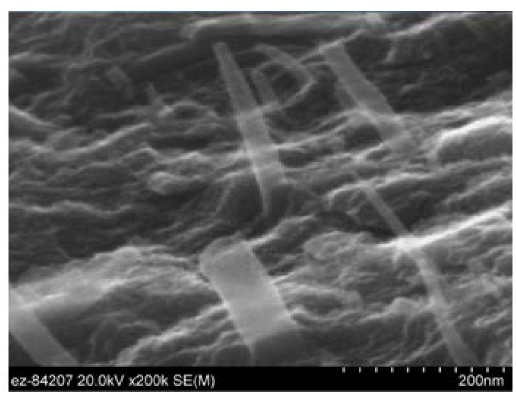












At no scale are CNTs agglomerated together. The orderliness of the CNTs placement is surprising uniform even at 200nm scale. The mixing of these CNTs was accomplished on a four mixer Elongator screw.

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[4] SUMMARY RESULTS OF A NOVEL SINGLE SCREW COMPOUNDER Keith Luker, Randcastle Extrusion Systems, Inc., Cedar Grove, NJ, Antec 2007

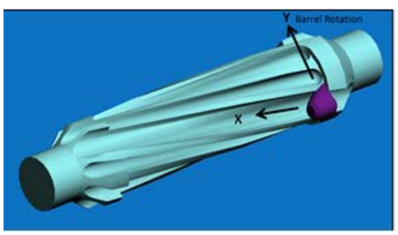
Conceptual Conclusion: We believe that an orderly mixing process can produce better results than a disordered, chaotic mixing process. We believe that the pictures above are evidence that the orderly mixing of an SSE can produce a better result than disorderly mixing of the CRTS.

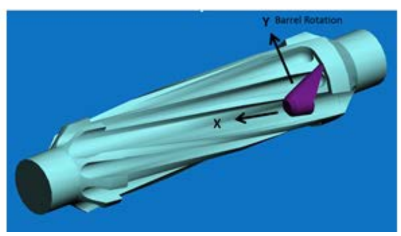
Method

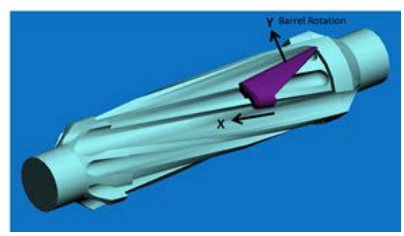
The SFEM Elongators employ a repetitive sequence of low intensity distributive mixing cycles within a mixer. Second, third and fourth mixers repeat the pattern. Each mixer exponentially increases the mixing. The ordering sequence for a Randcastle Elongator 3D mixer is x-y Stretch, y Shear, y Stretch, x-z folding flow. This is accomplished by:

Step 1: x-y Stretch:

- **Down Channel Pump:** Spirally pumping material down a first channel (or flute), axis x, *while simultaneously,*
- **Cross Channel Pumping:** The y axis drag flow (from barrel rotation) combines with the x axis pumping to elongate the material. Adjusting the cross channel flow so that it is greater than the down channel flow stretches *all of the melt input*. Cross channel pumping greater than down channel pumping reduces the pressure in the down channel pump to zero.

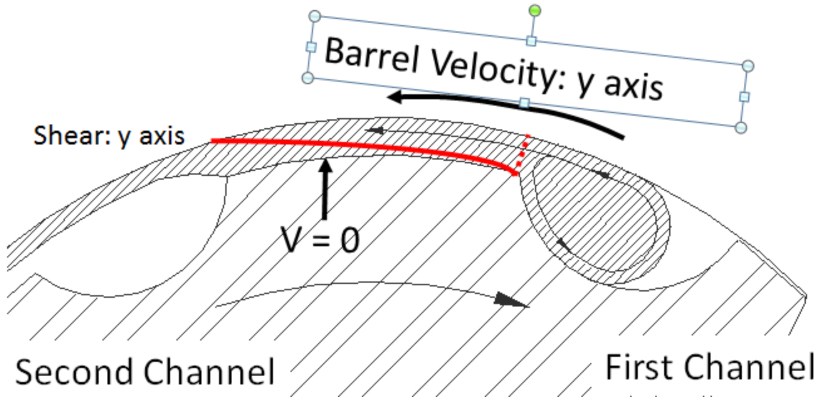






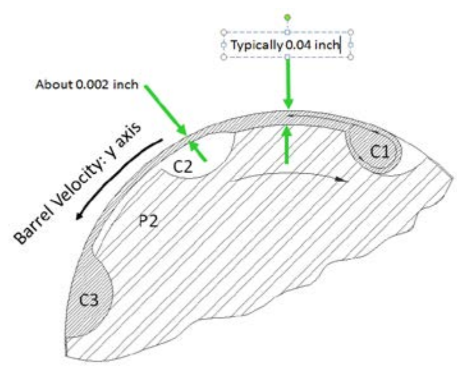
Step 2: y axis Shear:

- **Shear:** The material within the cross channel pump will be in simple shear (red dotted line and solid red line) as the input pressure is zero. Thus, the temperature rise from shear is minimized. All of the material experiences simple shear because the inlet and outlet pressure are zero. This serves to moderately reorganize the input along the y axis with minimal temperature rise. Note that shear exists because there are the two surfaces: The surface of the cross axial pump (where velocity is zero) and the surface of the barrel. The barrel drags material forward while the cross axial pump's surface restrains the flow.

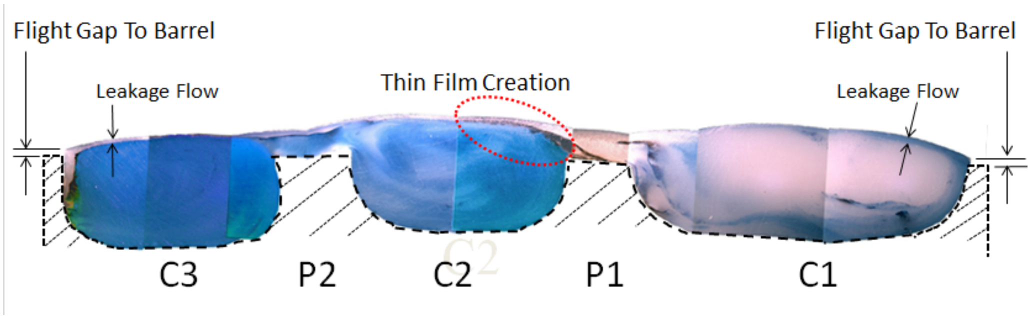


Step Three: y axis Stretch (and Degas If Necessary):

- **Remove The Restraining Surface Causing Shear:** Introduction of the second channel adjacent to the cross axial pump eliminates the restraining flow surface of the cross axial pump. The melt is still stuck to the barrel so the material exiting the cross axial pump is in a free state (on the screw side) and will draw down—i.e. elongate. Once unrestrained by the screw's shearing surface (where the velocity is zero), the barrel powerfully stretches the material from the typically 0.04 inch barrel gap into a very thin film. The thin film, with a lack of C2 filling as shown below, is especially easy to control by starve feeding the mixer. When such a thin film is created, degassing is greatly enhanced.



The creation of the thin film can occur even during flood feeding. Below, a flood fed extruder processing polypropylene with blue color concentrate was stopped; the screw was quickly cooled to freeze the material in the mixer.[5] The frozen material was removed from the mixer, cross sectioned and 9 photographs were taken and stitched together. The cross hatched area represents the mixer surface including the flights upstream and downstream. The thin film can be seen drawing down from the P1 shearing exit within the circled red oval:



- Note:
  - The exponential increase in stria. C1 shows little striation. C2 shows a tremendous increase in stria—the absence of the distinct C2 stria within C3.
  - Rotational flow as show by the stria beneath the thin film creation in C2.
  - The leakage flow. On the right, the leakage flow is blue and becomes clear. So, the material upstream of the mixer (in a conventional screw channel) first leaked clear material and then leaked blue material over the right flite which we see as a blue to clear boundary flow.

Step Four: x-z axis Folding:

- **Pump Material Into Exit Channel:** The barrel conveys the y stretched thin film (leakage flow, etc) into a third channel adjacent a downstream flight and adjacent an upstream cross axial pump. Below, flow from C2 enters P2. Unlike P1, P2's purpose is to pump and contain the flow so little mixing will occur.

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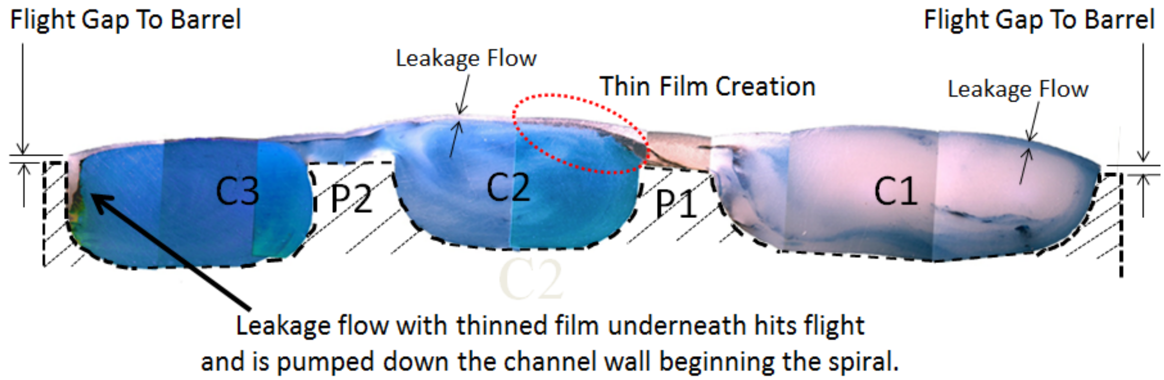
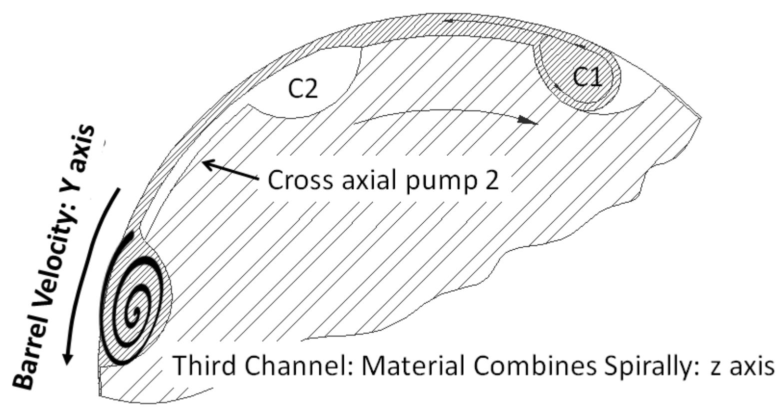
[5] **INVESTIGATION INTO A HIGH OUTPUT POLYPROPYLENE SCREW AND ITS MIXING MECHANISM**
Keith Luker, Randcastle Extrusion Systems, Inc., Cedar Grove, NJ
Thomas M. Cunningham, Extrusion Technical Services, Brodheadsville, PA,
Antec 2010



The thinned material, pumped by drag flow, will hit the flight and start to move down the channel. In the picture above, you can see the beginning of the process as the clear material (from upstream leakage flow) starts to move down the side of the screw. Eventually, it will rotate and spirally fold in the z dimension while flowing axially in the x dimension. This will be similar to the well-known output channel of a UC mixer.



Conclusions: Polymers are viscous and they behave in an orderly way. By eliminating chaos from the mixing process, a SSE can mix three dimensionally in an ordered fashion. This distribution has inherent advantages over the chaotic mixing inherently present within the twin screw extruder. The SSE can be a better distributive mixer than the CRTS.

It should be remembered that while the CRTS is dispersive (i.e. to break solids and some agglomerates), that the energy required to break an object increases exponentially. In the case of very small particles, particles that a CRTS cannot break, the 3D distributive mixing system for single screws will be superior.

There are many extruder mixing requirements that require distribution rather than dispersion and self-wiping (the two main assets that a CRTS over a single). Polymer alloying, fine mixing of immiscible polymer blends, mixing free flowing particulate, mixing of nano-scale objects, thermal and mixing of plasticizers.

Injection molding and blow molding both have screws. Fine mixing can be accomplished in historically short screws without the need for separate compounding and pelletizing—a significant cost savings. Without a second heat history, there is an opportunity for better properties.

The 3D Elongator compounding screws are available for all brands of extruders and molders.

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