Single Screw Extrusion: Principles and Screw Design

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Introduction: Until recently, single screw extruders (SSE) have little changed, in principle, since their invention around 1897. They are mechanically simple devices. A one piece screw, continuously rotated within a barrel, develops a good quality melt and generates high stable pressures for consistent output. These inherent characteristics, combined with low cost and low maintenance, make it the machine of choice for the production of virtually all extruded product.

Historically, the polymers and particulate they carry (including active pharmaceutical ingredients, API) are subjected to compressive, shear dominated deformation. Compression of particulates, such as API, forces the particulate together into agglomerations under very high pressure *before and during melting*. When this happens, shear deformation is insufficient to break the agglomerations into their constituent parts. Agglomerations within a polymer matrix define a poorly mixed product.

Many ingenious schemes are known to improve the basic screw. Since the 1950's, a variety of mixers have been available. Some of these force material into small spaces for additional shearing. Some divide the flow into many streams so that smaller masses are sheared more effectively. Some make use of pins embedded in the root of the screw and some cut the screw flights. Yet they have one thing in common that limits their effectiveness. They are placed after the screw melts the material—and most of a screw is necessarily dedicated to producing a melted polymer. Typically, these mixers are less than four screw diameters long.

Since the 1970's, various barrier or melt separation screws have become widely known. These force material over a barrier flight of reduced dimension (compared to the main flight). This prevents unmelted material from moving downstream. And, as the material moves over the barrier flight, it receives additional shearing and so is mixed a little bit better. Some screws force material back and forth across barriers which also slightly improves the SSE mixing.

To some degree, all of these inventions are incrementally successful. However, they do not change the fundamentals of compression and shear dominance in the SSE. So, until recently, the SSE remained an agglomerating machine.

Meanwhile, the twin screw extruder (TSE), and the parallel, intermeshing, co-rotating TSE[1] in particular, became the dominant continuous compounding mixer for polymers and particulate. This is because it works on fundamentally different and better principle: *It melts prior to the compression of the solids.* This means that it prevents agglomeration of the ingredients and has no need to then break up agglomerates formed by compression. Fundamentally, it is not shear dominated. Instead, material moving through the intersection of the screws is extended. Such

[1] Since this particular TSE dominates the market, the use of TSE hereafter should be understood to mean the parallel, intermeshing type.

deformation is elongational. Elongation, instead of pushing API particles together, *pulls them apart.* Therefore, unlike the SSE's discussed above, the TSE mixers (most commonly bi-lobal kneaders) make up a substantial amount of the total screw length.

However, the TSE has flaws. All the material does not moves through the intermesh region. Some material escapes down the channels without moving through the extensional fields. And, some material will see the intermesh many times. Thus, the key elongational history of the polymer and API will be uneven. Compared to single screws, the TSE is less pressure stable; compared to singles, the TSE does not generate high pressures. (When used with a gear pump to generate high stable pressures, the TSE requires a sophisticated algorithm that is very sensitive to small changes in the feedstock and the starve feeding system.)

Very recently[2], significant advances in fundamental SSE technology have changed the landscape. *Melting now occurs before compression.* So, there is then no need to break up agglomerates caused by compression. Single screws now have dominant elongational deformation. Unlike the TSE, all the material can consistently pass through the elongational mixers. Melting and mixing are started very near the hopper so that a significant part of the SSE's total length becomes a mixer. These new SSE's retain their advantages of simplicity and low cost. They can still generate high and stable pressures most suitable for hot melt extrusion (HME) production even when starve fed without a complex control system.

Ideal Compounding:

In order to understand the SSE for HME, we must understand compounding as we will necessarily have at least an API and a polymer. It is undesirable to have local concentrations of API or polymer in the product. Compounding means combining two or more ingredients. Good compounding has other requirements. The processed material should treat the material equally. It should not be overly mixed in one region and under mixed in another. And, mixing should apply the least amount of energy so as to limit degradation of the components. So, compounding means to take local concentrations and manipulate them into smaller concentrations of satisfactory size where satisfaction depends on the use.

Local concentrations will occur when polymer pellets are dry mixed with API. Each pellet is a local concentration that must be distributed to incorporate the API. The API can also be thought of as a local concentration that must be distributed within the polymer pellets. Local concentrations are immediately reduced when working with a powder/powder blend (compared to pellet/powder). The better the mixture, the easier it is for an extruder to further reduce the local concentrations. Nevertheless, no matter how well mixed two powders are, there will be local concentrations at some scale. The job of the extruder is to further reduce these

[2] The first paper that proved the dominant elongational flow in the SSE was presented in 2011 by Costeaux, Ref. 5.

concentrations. This cannot be accomplished through a purely compressive screw since that takes the mixture and, at best, maintains the dry mix quality.[3]

An ideal HME mixer would maintain ingredient quality during the compounding process. Both plastics and API degrade due to thermal and mechanical stress. To mix well, there should be an orderly progression through the mixing process that maintains the quality of the ingredients.

Thermally, a single heat history within the extruder, of the shortest possible duration, at the lowest temperature is preferred.

Mechanically, an elongationally dominated system, *where all the material has the same elongational history,* is preferred. This will minimize unnecessary mechanical degradation and decrease the thermal processing time to achieve the same result. The shear component of the mechanical system, since it builds excessive heat (compared to the elongational component), should be minimized.

Basics of the Single Screw Extruder:

Low bulk density polymer solids, often mixed with various forms of particulate (such as active pharmaceutical ingredients, API), most commonly fall from a hopper into a long, continuously rotated extruder screw within a temperature controlled barrel, Figure 1.

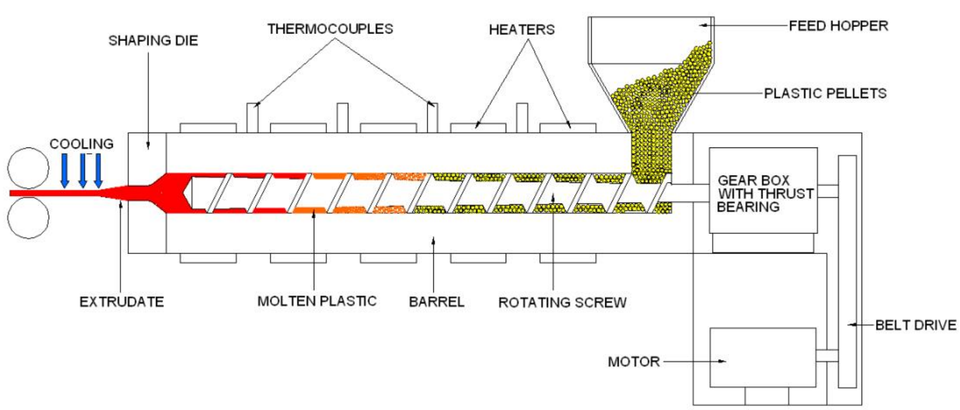


Figure 1

The screw forces the solid material into a decreasing space along the screw at higher temperatures. There the compressed material is pushed up against the heated container (the barrel). The compression both forces the air out the hopper and melts the material by pushing the material against the hot metal barrel. The dense/molten material is continuously pumped

[3] Compressive screws, in some circumstances, can take an orderly mix and agglomerate the ingredients. This will occur when the act of squeezing the mixture separates the ingredients. This is more common than is generally realized.

forward through a shaping die. The material exits the die where it is drawn down in a free molten state through a cooling medium until solid while continually pulled.

The key to the process is the extruder screw. While one may imagine many variations, the classic screw has a constant diameter. The modern screw length is usually 24 to 50 times its diameter. This is expressed as the length over diameter ratio or L/D ratio. Screws are, most commonly, made from a solid piece of steel leaving a screw root that is polished. The flights are ground and fit closely within the barrel.

Figure 2 is a general purpose polymer 24/1 L/D screw:

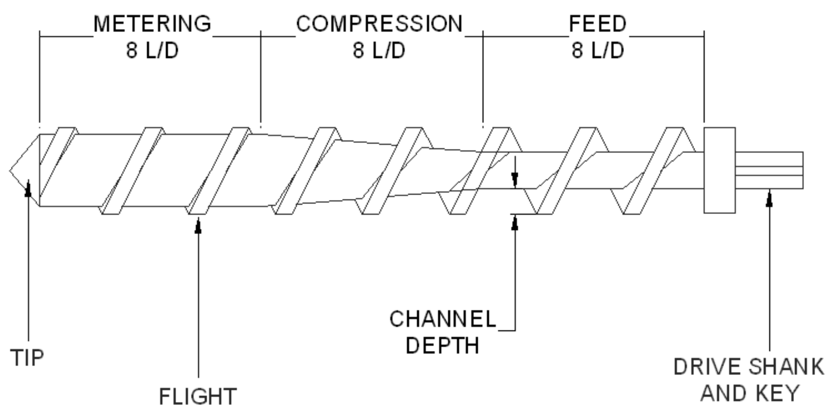


Figure 2

Typically, the one piece screw is driven from the right through a simple key on a shaft that fits into the gear reducer of the extruder. The general purpose screw has a flight pitch equal to the screw diameter. A classic general purpose screw has three parts all of equal length.

Most HME extruders are small and many are used for research and development. Sometimes, the very high API cost prohibits use by any but the smallest SSE's.

Plastic pellets for HME extruders are made in bulk. They are the same size for all extruders—often in the 1/8 to 3/16 inch range. This means that the channel depth must be sufficiently large for pellets to fit. Otherwise, the pellets will jam when entering the screw and such jamming can break the screw. So, screws with a 0.180 inches feed channel depth are recommended. Extruder for this drive system above are available for as small as 1 inch diameter.

For many HME applications, 1 inch extruders are too large because of the cost of formulation in the R&D phase. A second type of drive system is available. In Fig. 2, note that the root diameter of the metering section is much larger than the root of the feed section. The strength of the root increases with the cube of diameter. Thus, if the screw is driven through the metering section, the screw itself becomes much stronger since the highest torque is transmitted through the biggest root diameter as in Figure 3. The feed depth can then be kept at 0.180 inches with screws as small as 5/8 inch screw diameter. Since the output of an extruder screw decreases with the square of the diameter, a 5/8 inch extruder will only have one quarter of the output of a 1 inch diameter extruder.

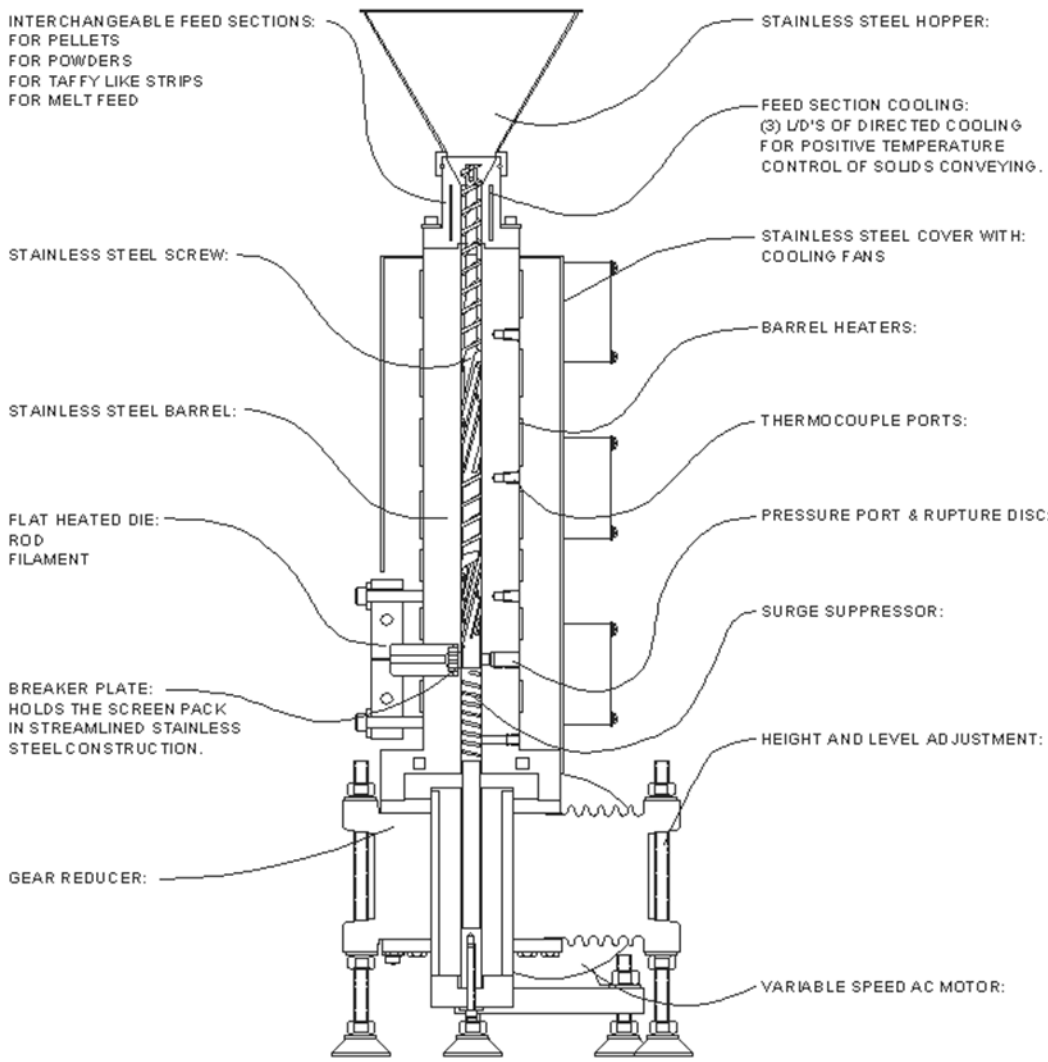


Figure 3

To prevent material from leaking into the gearbox, a special seal is used. This seal has a reverse flight compared to the main part of the screw. By making the pitch and channel depth small, it becomes much more powerful than the main screw and so becomes very effective. The HME material itself becomes the seal.

When the seal is made with one deep channel next to a shallow channel, material moves from the deep channel (the fill length is longer for a deep channel) and into the shallow channel and back into the main flow. This prevents stagnation.

Such seals are particularly useful for pressure stability. Since they act as an accumulator, they suppress small surges—variations in pressure and output (Ref. 1). Once the small surges are dampened, it can then be possible to use an automatic pressure controller to maintain the pressure as fine as plus or minus 10 psi in the barrel.

Below the 5/8 inch diameter, screws usually become too weak for the most common pellet sizes. However, smaller extruders are made including, 1/2, 3/8 and even 1/4 inch screws. These are built for free flowing powders or ground pellets. This puts the general lower limits for HME at about 10 grams per hour.

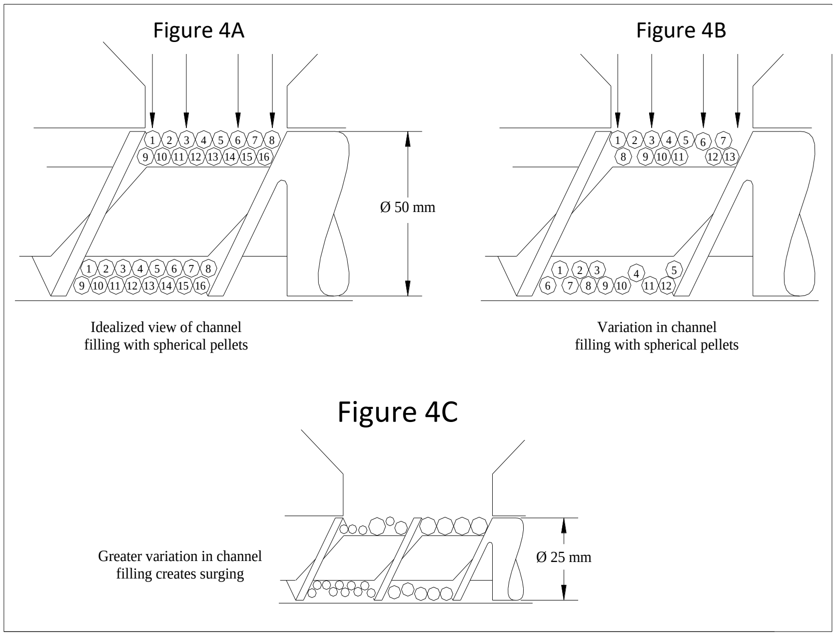
***Screw Feed Section*:** Referring to Fig. 2, the "feed" channel depth (and so the root diameter) is constant. The screw's feed section is associated with solids conveying. Thus temperatures in the screw's feed section are usually set[4] below the melting temperature of the plastic. If the temperatures are set too high, then the material will melt and conveyance (feeding) will stop. Pressure in the feed is usually very low and often zero as the screw is acting as a conveyor. Solids conveying needs little torque so, as a percentage of the total motor load, it is very small.

Temperature changes to the feed section of the screw can cause complex changes in extrusion behavior. Temperature changes can change the barrel friction which is the driving force for material transport along the screw which is resistive to flow. Therefore, the screw's feed temperature is usually optimized to control the solids conveying. This provides the most uniform pressure stability which is typically measured at the barrel discharge. When the pressure is unstable, the extruder is said to "surge" because changes in barrel pressure cause changes in output.

Changes in the screw's feed section temperature change the energy in the solids. Higher preheat temperatures (especially in smaller extruders) can mean easier material deformation within the decreasing channel of the melting zone along with lower torque which we see as a reduction in motor load.

Uniform feeding should not be considered a given. Consider the figures below.

[4] It is important to realize that all the temperatures along the screw are not set directly. Instead, the barrel which surrounds the screw is directly temperature controlled.

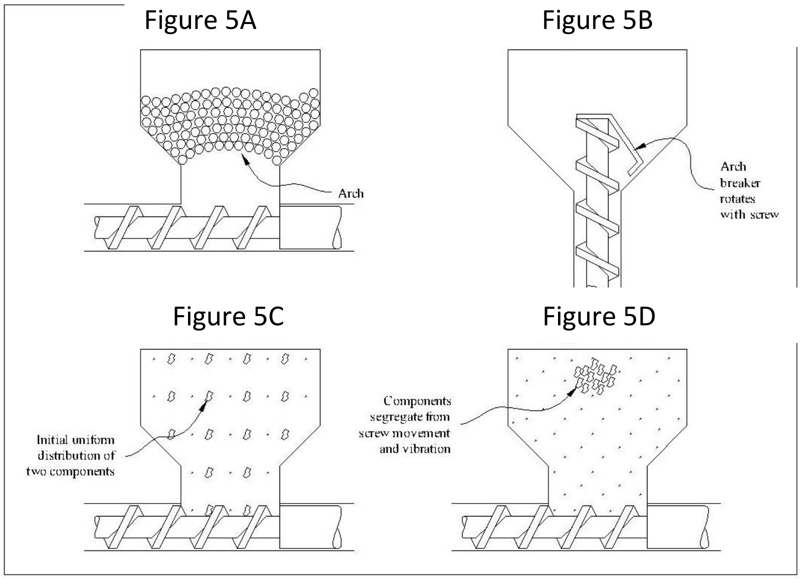


In 4A, an idealized view is shown with each of the perfectly spherical pellets falling perfectly into the screw channel—which is completely unrealistic. Figure 4B takes a step in a more likely direction showing gaps between the pellets and a small difference in the number of pellets between the top and bottom of the screw—12 to 13 or 8% which is not insignificant. Whatever variation exists in the first part of the screw is transferred, to some degree, downstream.

Figure 4C shows a more realistic variation in pellet size. One need only look at a handful of typical pellets to see significant variations in diameter—often the largest being twice the diameter of the smallest. If the pellets were spheres, the mass of the largest pellets would be eight times greater than the smaller ones! Figure 4C shows a large difference—not atypical—in mass in the two flights as will occur over time. In a large extruder, this would tend to average out. In smaller extruders, it will cause wide variations in mass transfer and make surging more likely.

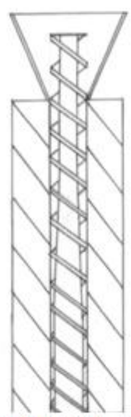
Other problems include arching or bridging over the opening as in Figure 5A and where feeding will cease. This problem can be lessened by adding a stirrer as in Fig. 5B. It is not only pellets that can arch over the opening but also powders. Ideally, HME materials should be free flowing so that they can easily move into the screw channel. When poured onto a flat plate, they should have an angle of repose of less than 45 degree (Ref. 2). If the angle is much greater, there will be a tendency to compact within the feed section of the barrel or the hopper.

It should not be assumed that a uniform mixture in the hopper will reach the screw channel in the same uniform mixture. Preferential feeding (because of ingredient size or geometry), the motion of the screw or vibration can change a perfectly uniform mixture, as in 5C, and de-mix it before it can reach the screw channel. The can be solved by starve feeding (reducing the input to the screw to less than the maximum it can take by gravity) with multiple feeders.[5]



ansportation, Figure 6.

Figure 6: Visualize A Stationary Screw and Rotating Barrel And Consider Friction



Conveyance occurs when barrel friction on the material mixture is higher than the screw's resistance.

Once the material has moved into the screw channel, it is propelled down the screw by friction. However, it is not the screw's friction that drives material forward but the barrel's friction. In Figure 6, we imagine the screw is stationary and the barrel revolves around the screw.[6] It is clear that the barrel's friction contacts the mixture and would drag it in a circle but, since the screw flights are in the way of circular rotation, the material is dragged forward against the screw.

[5] This will reduce the quality of the input mixture which puts greater demands on the extruder compounding.
[6] This is not done in practice but the material does not "know" which is turning.

This is not a very positive system when compared to positive displacement pumps and it is easily defeated. Since higher barrel than screw friction is required, anything that reduces barrel friction will change, or even defeat, transport. For example, the addition of a small amount of a slippery liquid to a pellet/API mixture will lubricate the barrel. The screw's resistance can then be higher than the barrel friction and forward motion will stop.

Another important consideration for HME extrusion is the density of the feedstock. Pellets are the most common feedstock for extrusion. However, for HME extrusion, there is a natural desire to work with ground or powdered polymers so that the input mixture is better mixed. This reduces the bulk density of the feedstock by introducing more air into the mixture. If again we imagine a lowered bulk density mixture entering the screw channel as in Figure 6, the barrel friction is again reduced until it becomes so low that there will be insufficient friction to overcome the screw's resistance. Then flow will stop.

While the feed section is particularly sensitive to changes in friction, material is driven forward by friction in all parts of the extruder. It should be recognized that friction is poorly understood and that within the HME extruder, friction is very complex changing with temperature and local conditions.

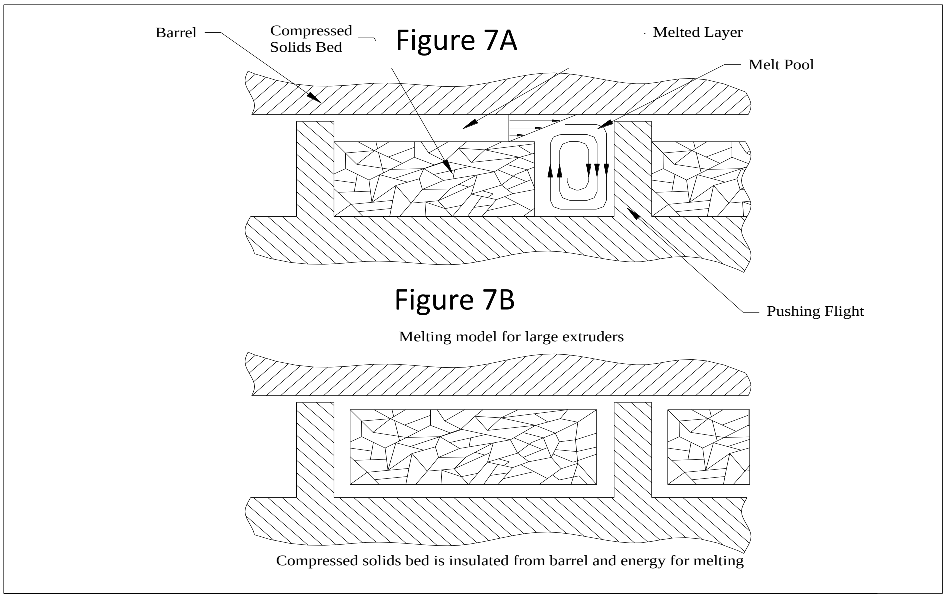
Screw Compression Section:

The next third of the general purpose screw is the compression section. It is sometimes called the transition section. It has a channel depth that diminishes over its length to one third of the channel feed depth. It is then said to have a 3:1 apparent compression ratio (ACR). This part of the screw is associated with melting and removal of air which is pushed out the hopper. Temperatures are typically set to allow ready deformation of the material. This is necessary because the space along the channel is decreasing and, if the temperatures are too low, material will jam in the screw. Most such jams are temporary but this stopping and starting is largely responsible for surging. The jamming is reflected in higher screw torque which we see as higher motor load.

The ACR must be high enough to squeeze out the air from the feedstock but not so high as to prevent material flow to the next section.

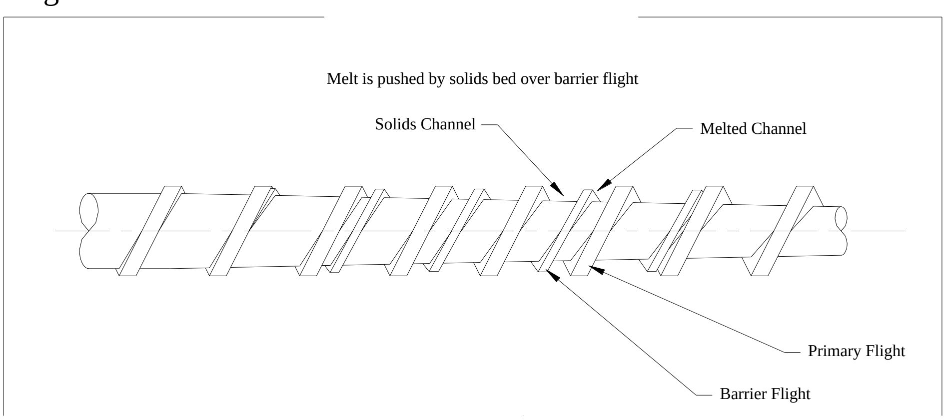
The lower bulk density of some HME mixtures also requires a change to the screw. Since there is a lower bulk density in the feed flights, there is also less mass. A 3:1 ACR is general-purpose only because pellets are the most common feedstock. So, these dense pellets, generally, will fill the screw once the air is removed during compression and create a stable flow. However, once the bulk density is reduced as described, the 3:1 screw will no longer deliver sufficient material to fill the screw in a stable fashion and the output is likely to surge. Generally, for reduced bulk density powder/powder mixtures, a 4:1 ACR would be typical.

As material is compressed, it is pushed up against the metal barrel and forms a solids bed. It is easy to see that API particulate would be compressed into agglomerates between parts of the solids bed. The portion of the solids bed that is pushed up against the heated metal quickly transfers its energy to the polymer-API mixture and a melted layer forms. Since the polymer beneath this layer is insulated by the melted material itself, heat transfer to the rest of the mass in the channel is slowed. Before it can melt, it is scraped by the advancing flight as in Figure 7A.



As screws become larger, the heat transfer from the screw root and flights also transfers energy to the outside of the solids bed, as in 7B, resulting in a cold compressed solids bed that "floats" within melted material. The solids bed is now isolated from metal contact and developing a good quality melt is unlikely if this solids bed simply proceeds down channel.

The solution to the problem is to drain the melt as quickly as it occurs as in Figure 8. These screws are called melt separation screws[7] The oldest, the Uniroyal design, is shown here but a variety of designs are available.



[7] It is common to call these screws "barrier screws." However, barrier screws can have other purposes besides separating the melt from the solids bed and for mixing in particular.

Figure 8

A common problem with barrier screws is compaction of the solids bed such that the solids bed stops moving. This prevents the continual flow of material movement through the screw. This compaction can occur anywhere along the barrier but is most likely at the beginning and end of the barrier. This can cause surging, gel showers, carbon specs and loss of output. Han et al (Ref. 3) showed that the removal of part of the first barrier could prevent these problems in some circumstance.

Nevertheless, it should be noted that barrier screws increase the compressive force on API with a greater tendency towards agglomerations.

Screw Metering Section:

Flow through a metering section is a spiral flow moving down channel. It is represented in Figure 9.

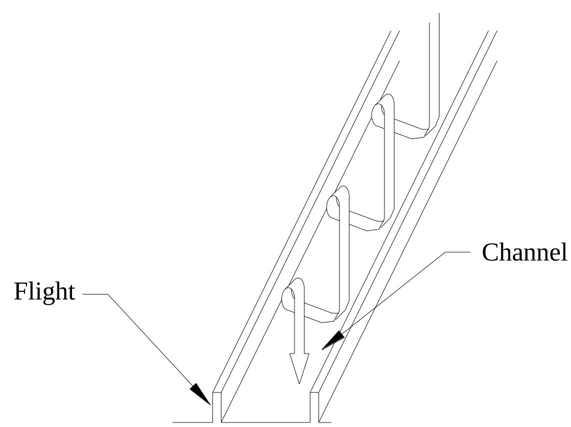


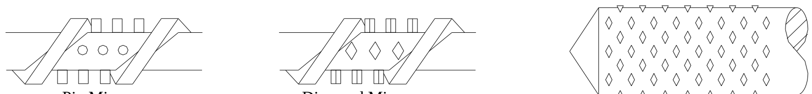
Figure 9

The material closest to the root moves slowly up the sides of the flight; then it moves across the barrel; finally, it moves down the other side of the flight and back across the screw root. Meanwhile, material centermost in the channel moves more quickly downstream. Thus the metering section mixes, though only in a very limited way, the polymer and API.

A wide variety of mixers can be added before, during or after the metering section either in general purpose screws or melt separation screws. Most of these are distributive mixers with little claim to dispersive capability. They fall into several categories.

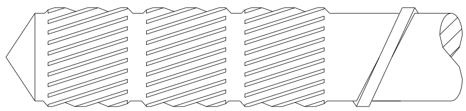
Mixing Pins: Pins can be placed between flights, most commonly round or diamond shaped, or in lieu of flights as in Figure 10. Pins are often made small in diameter because the more pins, the more combining and recombining of the flow. However, small pins will bend and can fatigue over time and eventually break. Round pins tend to have a stagnant area behind them hence other shapes such as diamonds are used. It should be noted that unless the diamond is properly oriented in the flow and very close together, they too will have stagnant zones.

Figure 10



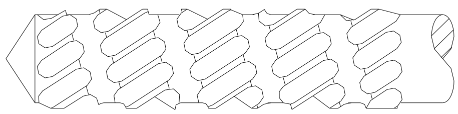
Pin Mixer Diamond Mixer Pineapple Mixer

Figure 11A



Dulmage Mixer

Figure 11B

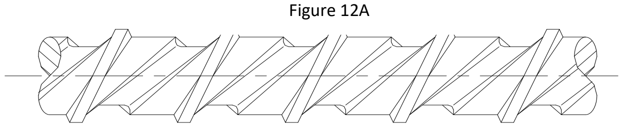


Saxon Mixer

Slotted Mixers: Figure 11A and 11B show common slotted mixers. The flowing materials are separated into many streams to reduce their large mass into smaller portions. Because of screw motion, these smaller masses rotate in the channel to the barrel. This allows for some heat exchange before the flows recombine.

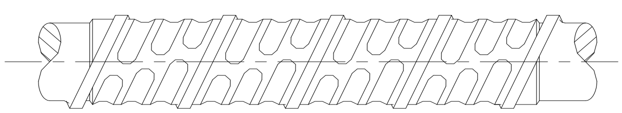
Variable Depth Mixers: Figure 12A and 12B show variable channel depth mixers.

Figure 12A



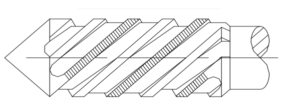
Pulsar

Figure 12B



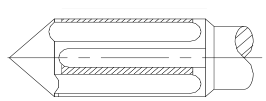
Strata Blend

Figure 13A



Egan Mixer

Figure 13B



UC Mixer

Shear Mixers: Figure 13A and 13B show two long established mixers where materials are forced through narrow slots for additional shearing.

Invariably, the question becomes which of these mixers is the best mixer and under what circumstances?

The most consistent testing has been by Dow Chemical using the same procedure to compare various screws and mixers. ABS resin is compounded with about 12% white pigment to form an opaque background and pelletized. Then, black color concentrate pellets are added at 0.5% to 3% to the compounded pellets and a strand is made. When the strand is sectioned, black spirals (the spirals are from the rotation of the screw) appear. Screws with the least distinct spirals are judged best.

At Antec 2010, the author reported (Ref. 4):

> Very consistent mixer studies include the Maddock [1, 6], Stratablend (trademark New Castle) [2], Energy Transfer [3], Variable Barrier Energy Transfer [4], and the DM2 with Eagle Mixing Tip [5]—generally referred to as high performance screws. One study even includes the more complex Twente mixing ring, the Barr sleeve mixer and a Barr ring mixer [6]. These papers describe a spiraling pattern in the extrudate.

All the screws and mixers lessened the distinct spiral pattern of the control screw somewhat. However, spiraling patterns were still easy to see in all screws.

SSE Elongational Mixers:

A member of the newer class of elongationally dominant screws was tested using a similar procedure of testing black color concentrates against a pigmented background. This screw has a series of three spiral flow elongational mixers (SFEM) on the screw and is called an Elongator. Even at 200 times magnification, no spiral patterns were found.

This is not surprising. Previous work had been presented showing much finer scale of mixing than spirals in rod seen by eye. For example, in 2007, polystyrene was mixed in PE and shown to disperse to 5 micron scale, carbon nano-tubes were mixed to the 1 micron scale and ceramic particulate to the 500nm scale (Ref. 5). The same study showed that levels of inert ingredients could be incorporated at up to 35%.

While pictures at very high magnification are helpful, quantitative mixing comparisons have remained elusive. However, at Antec 2011 (Ref. 6), Costeux presented a paper that quantified mixtures from four different processing tools. It also convincingly shows, too, that the SFEM Elongator is dominantly elongational based on its ability to finely break down blends with high viscosity ratios that cannot be dispersed by shear only.[8]

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[8] The full explanation does not belong in this chapter. However, for those particularly knowledgeable readers, reference 5 says, "The fact that droplets in the HM 7280 blends which have the highest

Two batch mixers (a Haake Rheomix 900 bowl mixer and a Randcastle SFEM-1 batch mixer) were compared with a twin screw extruder and the Randcastle SSE with SFEM Elongator screw. An atomic force microscope (AFM) was used to examine the samples and the minor phase domains were then digitized. Mixing was quantified by digitizing the domains of the minor phase and applying image analysis to extract three dimensional domain distributions. This allows the calculation of volume and a very simple comparison as seen in Figure 14 (Courtesy of Dow Chemical, Antec 2011). The numbers indicate the melt index of the PE component in the 70% PP 30% PE blend.

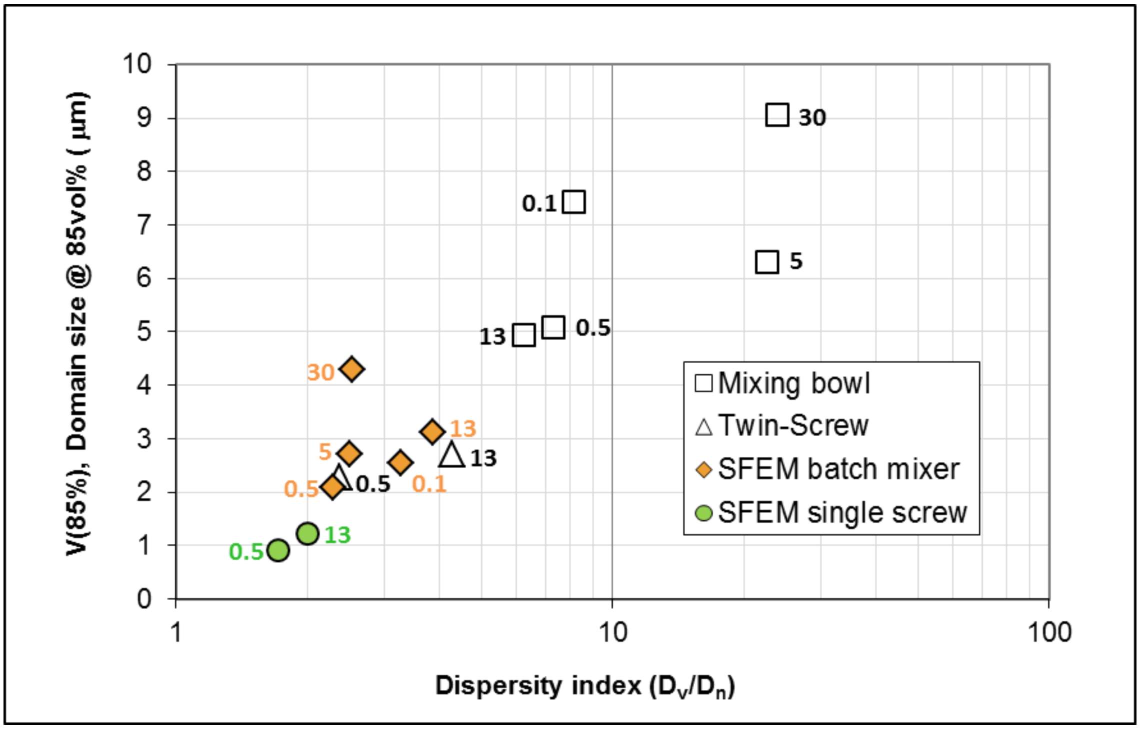

Figure 14

The volume of a sphere decreases rapidly with diameter. If the diameter of a sphere is reduced by half, its volume is reduced by 1/8. So, if the mixing bowl makes spheres with a diameter of 5 microns (as in the 0.5 MI material) they will have volume of 65.5 cubic microns. Both the twin screw and the SFEM batch mixer made 2 micron diameter spheres of the same material with a volume of 4.2 cubic microns. Therefore, they both made 15 times as many smaller spheres for every one sphere that the bowl mixer made. It can then be said that the twin and SFEM batch mixer compound 15 times better than the mixing bowl.

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viscosity ratio (estimated λis 4.8, larger than the shear break-up limit of 3.5 and the lower compatibility with PP are dispersed supports the claim that the flow in the SFEM is primarily elongational, based on the Grace plot...)

Likewise, since the SFEM-Elongator screw mixer, for the same material, made 1 micron domains (a volume of 0.5 cubic microns), the SFEM-Elongator mixed 8 times better than the twin.

So, this new class of mixers can mix particulate and polymers in ways that have not been possible previously.

There are two types of elongational mixers: The SFEM (spiral fluted elongational mixer) Elongator and the AFEM (axial fluted elongation mixer) Recirculator, Figure 15. The AFEM Recirculator has a first axial channel (C1) next to a first pump (P1). P1, while it has the same geometry as a barrier, has a different behavior than a barrier. A barrier screw forces material over the barrier in an attempt to shear the material. This requires a great deal of pressure. However, if the pressure is low in the channel, then the same barrier geometry becomes a pump which pulls on viscous materials.

Elongational flow is created as the material moves down the first channel (pushed down the channel by pressure flow) and pulled by the pump by drag flow at an angle. The pressure flow can be thought of as a vector moving down channel (parallel to the screw axis) and the drag flow of the pump as a second vector pulling the viscous flow at 90 degrees (at right angle to the screw axis). The combined vectors is 45 degrees which becomes stretched flow as in Figure 15. The figure shows an AFEM-Recirculator with two groupings composed of C1, P1, C2, P2, C3. One grouping is on the rear side and is not visible in the figure.

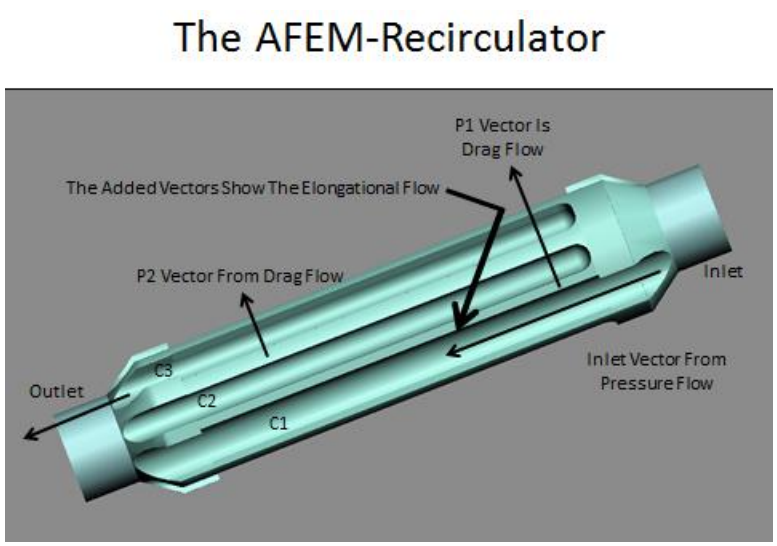


Figure 15

When the pump's capacity is higher than the input to the channel, 100% of the material is stretched as it moves to the pump. The drag flow's pumping capacity is easily kept higher than the input to the channel by starve feeding. The fill length of C1 will lengthen or shorten depending on the amount of starve feeding.

A colored section of material (representing a local concentration of API)—surrounded by clear material entering C1—will be drawn by P1 at the entry as in Figure 16. This section will start to deform as shown in Figure 16A into a plane. As the local concentration moves down the channel, the mass in the channel is reduced and the plane becomes larger as in 16A. Eventually, the entire local concentration of API is converted into a plane. This can be thought of as the short cylindrical local concentration becoming a wider and longer plane.

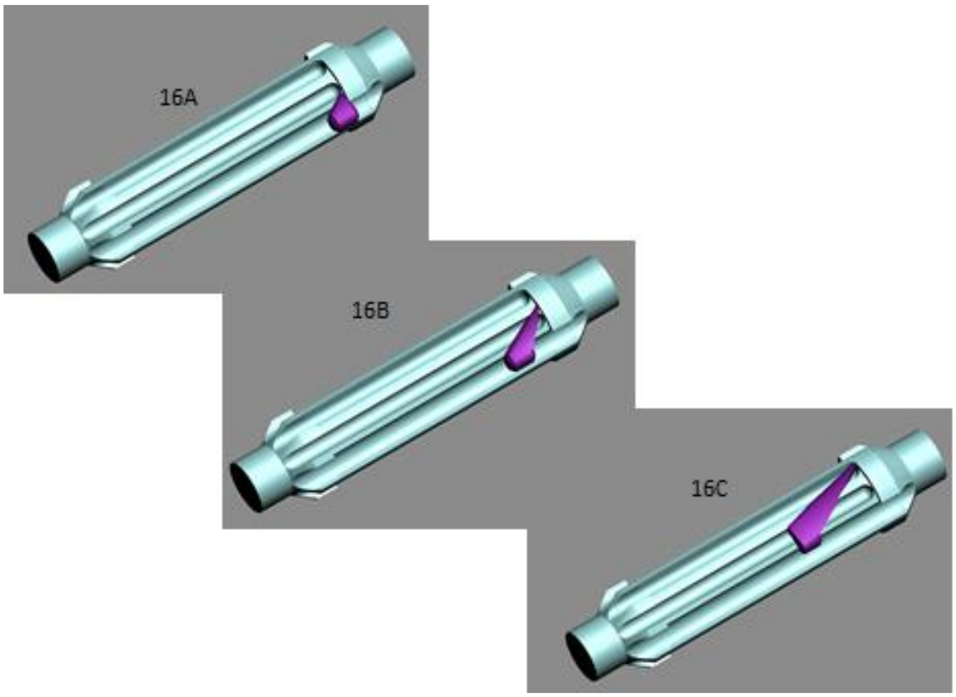


Figure 16

The length of the plane, compared to its width, increases as the C1 channel is increasingly starved. The width can increase to the limit of the P1 pumping capacity.

The process begins as material moves down the C1 channel, as in Figure 17. Because the pressure is zero in C1, the flow over P1 is nearly "pure" shear. This is very unlike the flow over a barrier flight which is primarily pressure flow that is necessary to force material over the barrier. Pressure flow does not contribute much to mixing. Instead this "pure" shear flow reorients the material as the material sticks to the barrel and the screw. This reorganizes the flow moving material at the barrel away from material near the screw to further distributes the API.

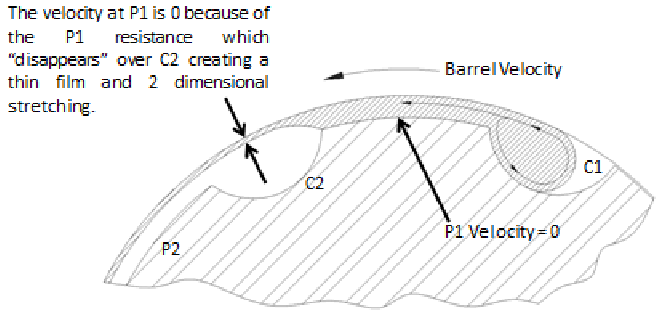


Figure 17

After the shear flow, material reaches a second channel, C2, which lowers the screw's resistance drastically on the material near the screw. However, it does not change the adhesion to the barrel. This creates a powerful two dimensional stretching and converts the material into a thin film as shown in Figure 17.

The thin film at zero pressure is useful for degassing when a volatile is present. A hole can be placed in the barrel and the gas extracted from the thin film—preferentially with the application of a vacuum. Qualitatively, this is much better than the conventional two stage screw where the gas must be extracted from a large mass on the pushing side of the flight. And, quantitatively, multiple vents at each mixer are possible.

Material then enters the third channel and exits.

When a flight is not connected to the end of the AFEM-Recirculator, the material will move by pressure flow towards the downstream flight. The pressure may also push material in the empty end (the end away from the hopper) of the C2 and C3 channels. In this case, some material can then move upstream in the C2 and C3 channels and recirculate. The amount of recirculation depends on the distance from the AFEM-Recirculator to the downstream flight and the amount of C1 fill. If the C1 channel is very starved, there can be more recirculatory flow than input flow. This is usually only advantageous for extremely difficult mixing problems (such as nano compounding) rather than HME applications. If the C1 fill is greater than the capacity of P1, then there will be no recirculation and material can exit C1.

There is another useful feature of the AFEM-Recirculator. During an upward surge in pressure, the fill length of C1 will lengthen and will shorten during the trough of the surge. Therefore, the mixer will act as an accumulator and will dampen pressure and flow instabilities. Each additional mixer increases the dampening to make the final flow surprisingly stable even when the screw is starve fed.

The second type of screw in this class of elongational mixers is the SFEM-Elongator, Figure 18. The design is very similar to the AFEM-Recirculator but is a pitched design and has flights connected to each end of the mixer. The pitched flights increase the forwarding ability of the screw which minimizes the residence time within the screw. The additional forwarding is useful for vented applications. The connected flights mean that the output of any channel flows immediately moves onto a flight and then the material moves downstream. Thus, recirculation does not occur. This makes the SFEM-Elongator better for most HME applications.

Figure 18 has two sets of C1, P1, C2, P2, C3 surrounded by a flighted clearance.

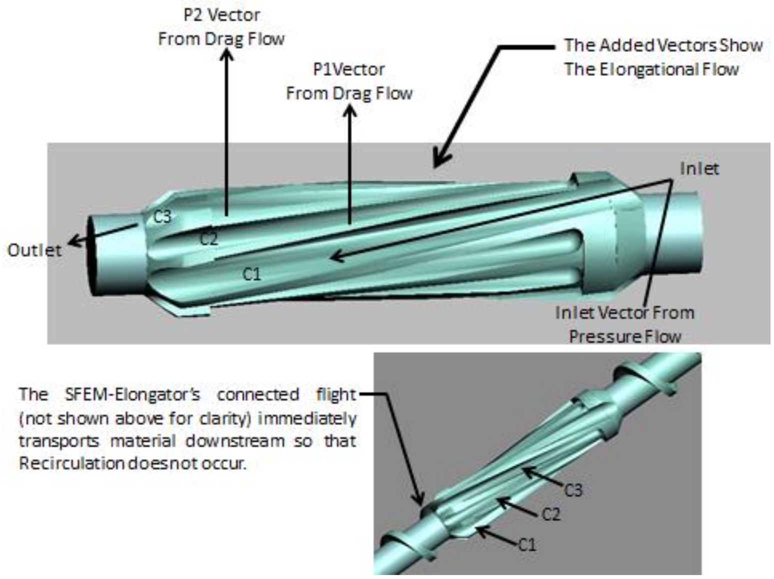
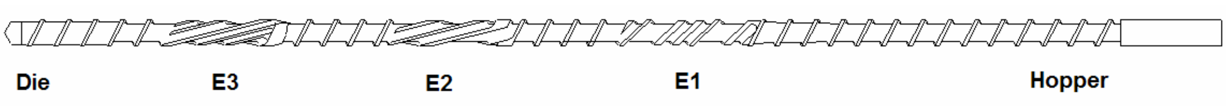


Figure 18

Most of the principles outlined for the AFEM-Recirculator apply to SFEM-Elongator. That is, the first channel has three dimensional elongation; the first pump has shear undiminished by pressure flow to reorganize the material top to bottom; it has two dimensional stretching as the material moves from P1 to P2 over the second channel. When the material is pumped from C3, the material moves immediately onto the connected downstream flight and is forwarded so that recirculation does not occur keeping the residence time short.

The stretching flows in the channels have been observed. This is done by mixing color concentrate into the polymer, stopping the screw and cooling the material as quickly as possible on the screw. The stretching flows are preserved by the color within the cooled pullouts. This is more easily observed for flood fed conditions where the C2 channel is filled. This makes extraction of the cold screw and subsequent sectioning easier. Figure 19 shows the schematic of the SFEM-Elongator screw.

Figure 19



The thick frozen section, Figure 20, is from the second of three Elongators, E2, where 2% blue color concentrate was mixed with polypropylene (Ref. 7). The arrows point to the material's movement downstream within the channels. Traces of color on the root of the screw show the angle of rotation within the C2 and C3 channel.

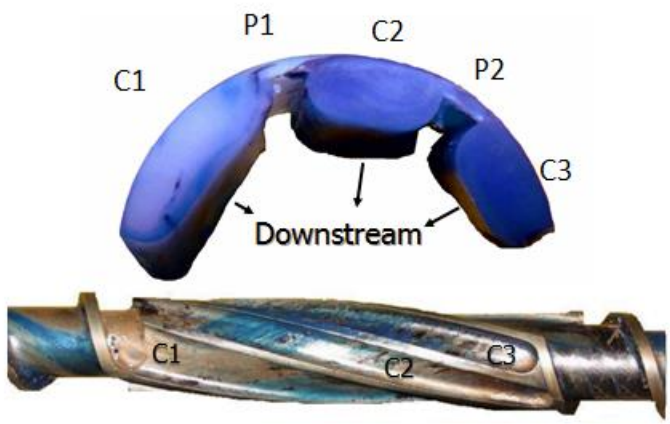


Figure 20

Figure 21 is the same cross-section as 20 but thin sectioned and magnified for additional detail by stitching together 8 separate pictures.

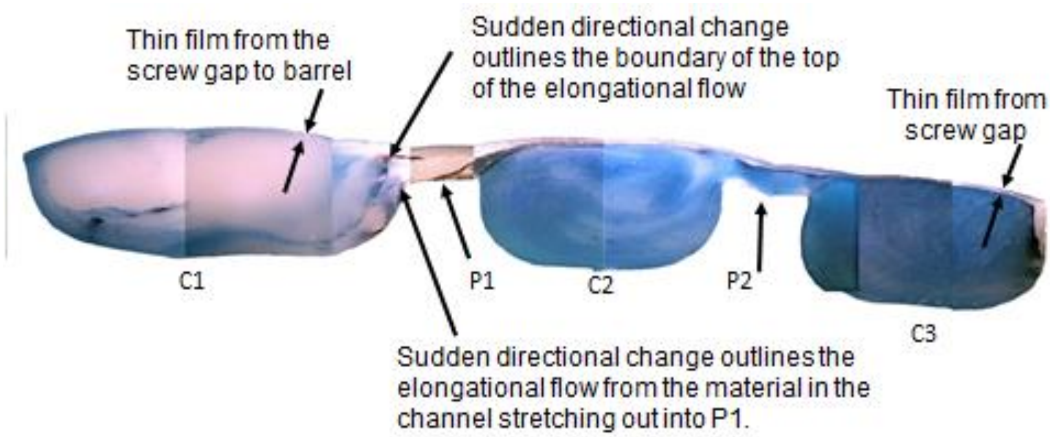


Figure 21

A dramatic difference in the quality of the mixture is seen as the material moves from C1 to C2 and again from C2 to C3.

To the far left and far right of the cold pull out in Fig. 21, would be flights of the screw. These flights have a clearance to the barrel of about 0.002 inch. Material "leaks" through the gap and is seen as a thin film. This film is dragged along by the barrel through the mixer until finally disappearing in C3.

In C1, the individual pellets are not visible as they are in a typical compressed solids bed of material. Instead, the material, having flowed through E1 and the following channels, arrives in C1 as a highly viscous melt.

Material in C1 is then dragged to the right towards P1. The two arrows within C1 outline the boundaries of the elongational flow as the material approaches P1. Within P1, shear flow occurs. Immediately after P1, the exiting material is dragged into a very thin layer just beneath the leakage flow material. This is the stretching flow that is primarily two dimensional and greatly extends the material because of the high barrel velocity. The thickness of this stretched material appears much less than the leakage flow thickness.

A similar process occurs as material moves from C2 and approaches P2, see Figure 22, as outlined. Material over P2 must now contain the material in C3 so it is not sheared in the same way as P1 as can be seen by the flow lines in P2 and the change in the leakage flow dimensions. The material near the output of P2 elongates and converges as shown by the dotted lines. This is similar to the flow immediately after P1.

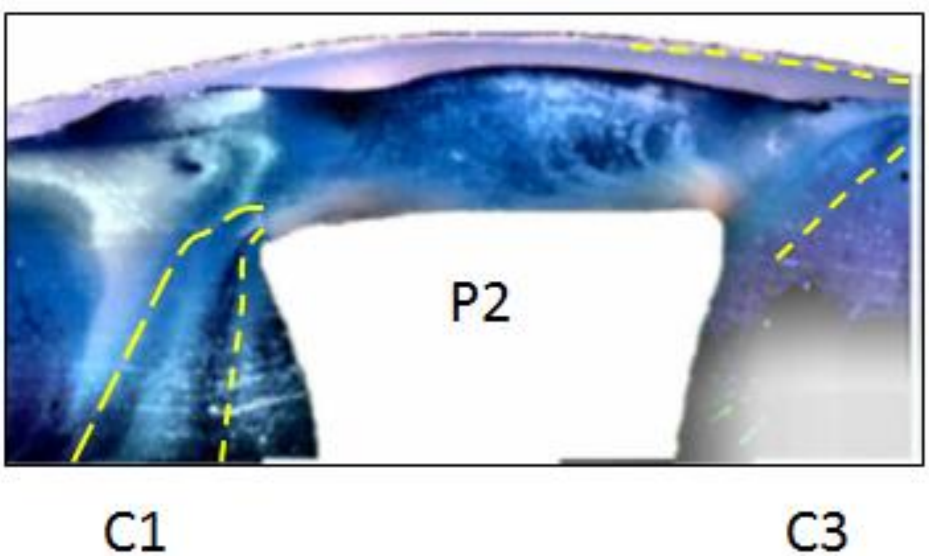


Figure 22

In an HME extruder, starve feeding is preferred to flood feeding. Flood feeding fills the screw to its maximum capacity from the hopper. Flood feeding can allow compression of the API before the first SFEM-Elongator and can cause agglomeration.

Starve feeding uses various volumetric feeders or gravimetric feeder to limit the flow into the screw. Because the flow in the solids channel is less than the capacity of the screw, the partially empty channel has no pressure on the API. This prevents compression and agglomeration before the material enters C1. By feeding at a rate less than the P1 capacity, C1 will empty, C2 will not fill as in the flood fed example above, and all the processed material will move into C3. It will then have the same thermal and mechanical processing history. Since the system is elongationally dominant (rather than shear dominant) it will have the lowest energy input to accomplish the mixing.

Summary:

To compound means to all the mix ingredients with the same thermal and mechanical heat history using the least amount of energy. A bell curve showing the number of mixing cycles does not describe an orderly mixing process. But, that is what the TSE does—and the more mixers you add to it, the greater the disparity between the overly mixed and the non-mixed ingredients. A good HME compounder requires a mixer that orders all the input in a predictable fashion.

The SFEM-Elongator SSE is an orderly compounder. It accepts a disorderly mixture with local concentrations and methodically organizes it by elongating all of the input. The modern elongational SSE limits the amount of mixing to what is needed to achieve a certain goal. Because of its ability to exert elongational forces from the beginning of the cycle, the proper amount of mixing can be applied which limits the thermal and mechanical processing history.

The SSE is a low cost processor that can compound and develop sufficiently high and stable pressures to make HME product from a single heat history. The dominance of the elongational flow reduces heat generation limiting thermal degradation. The recent advances in elongational technology make the SSE an ideal choice for HME applications.

September 10, 2021: Since this paper was written, Randcastle has pioneered new, unrivaled mixing technology. See The Molecular Homogenizer.

References

1. Luker, K, *Surge Suppression—a New Means to Limit Surging*, Antec 1995.
2. Rauwendaal C., Polymer Extrusion, NY Hanser Publishers, 1986, page 169.
3. Han, KS et al, *Elimination of a Restriction at the Entrance of Barrier Flighted Extruder Screw Sections,* Plastic Engineering Magazine, April 1996.
4. Luker, K, *Comparison of Flow Striations of Various SSE Mixers To the Recirculator and Elongator Mixers,* Antec 2010
5. Keith Luker, *Summary Results of a Novel Single Screw Compounder*, Antec 2007
6. Stéphane Costeux, et al, *Facile TPO Dispersion Using Extensional Mixing*, Antec 2011
7. Keith Luker, Thomas M. Cunningham, *Investigation into a High Output Polypropylene Screw and its Mixing Mechanism,* Antec 2009.