NEW INVOLUTE EXTRUDER SCREW ELEMENTS FOR IMPROVED PRODUCTIVITY AND QUALITY

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Abstract

The co-rotating fully intermeshing twin-screw extruder has evolved significantly in the 60 plus years since it was commercialized in 1957. While this equipment might be considered a "mature" technology, it has not experienced a decline in new developments as might be expected, but rather a significant number of advancements. The technology continues to evolve. For example in the last 20 years several significant developments have been introduced. These include a) the implementation of high torque (power) designs, b) the use of increased screw rpm in conjunction with high torque for improved operating flexibility and productivity, and c) a breakthrough technology for feeding difficult to handle low bulk density materials. However, one area of twin-screw technology that has not evolved as much is screw elements geometry. Conveying elements and kneading blocks have remained essentially the same since the original Erdmenger design patents filed in the late 1940's and early 1950's. However, to take advantage of increased torque and power transmission capacity introduced in the latest generation of twin-screw compounding extruders, solids feed conveying and melt/mixing capacity in, for example, some highly filled compounds, had to be improved. Coperion has developed special series of screw and kneading elements with a new Involute cross section (Patent: EP 2 483 051 B1) design to help achieve this objective. This paper will focus on the comparison of standard kneading blocks vs new involute kneading elements, specifically looking at some significant aspects related to performance.

Introduction

The co-rotating fully intermeshing twin-screw extruder has evolved significantly in the 60 plus years since it was commercialized in 1957. While this equipment might be considered a "mature" technology, it has not experienced a decline in new developments as might be expected, but rather a significant number of advancements. The technology continues to evolve. For example in the last 20 years several significant developments have been introduced. These include the implementation of high torque (power) designs, the use of increased screw rpm in conjunction with high torque for improved operating flexibility and productivity, and a breakthrough technology for feeding difficult to handle low bulk density materials. However, one area of twin-screw technology that has not evolved as much is screw elements geometry.

Kneading blocks, while acknowledged as the backbone of the screw configuration with respect to melting, particle distribution, aggregate dispersion and resultant overall product quality, have remained essentially unchanged for more than 60 years. Figure 1 shows a comparison between the original 2-lobe kneading block design published in German Patent 813,154 granted to Rudolf Erdmenger in 1951 (priority date of September 20, 1949) and a current 2-lobe kneading block.

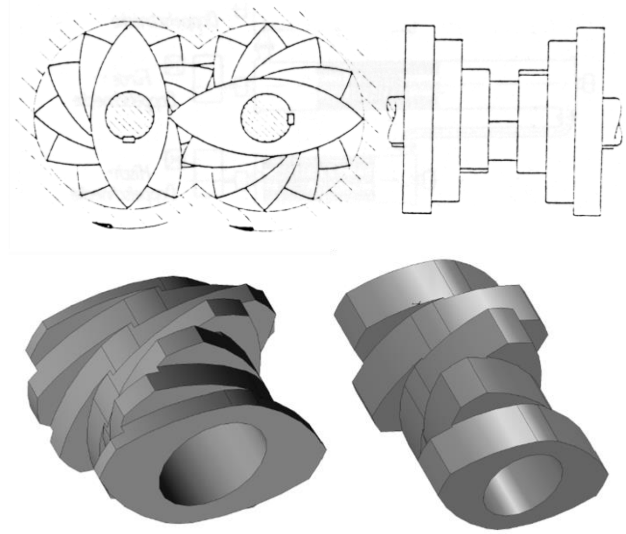

Figure 1: Comparison of original kneading block design (top) vs. the current standard kneading block (below).

The first and primary claim of the basic patent for threaded screw by Erdmenger is extremely informative. It succinctly describes the geometry for double or multiple-shaft co-rotating extruders in single or multiple-flited versions with a sealing profile, i.e., the flank profiles are defined in cross sections by circles with radius equal to the centerline distance of the shafts. While the patent application was filed in 1944, this patent was not issued in West Germany until 1953 and was given a five-year post-war extension of validity (23 instead of 18 years; valid until 1967). The second and final claim (Figure 2) defines a geometry where disc width is progressively increased (for the purpose of improving the dispersive mixing effect) along the axial of the element. There is a corresponding increased width groove in the element on the neighboring shaft. The progressive geometry has lost its significance with the subsequent invention of simpler, more efficient kneading discs [1]. Several of these will be described below.

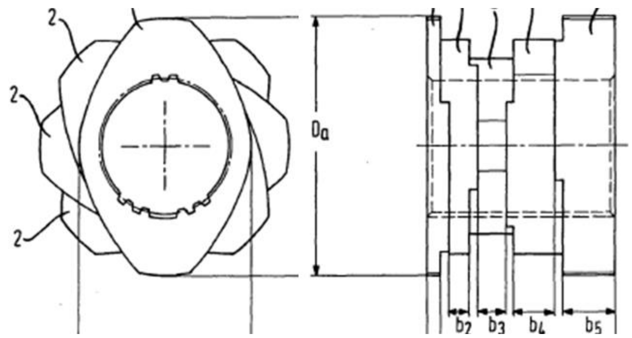

Figure 2: Progressive kneading blocks for combined distributive and dispersive mixing as described by Erdmenger

This is not to say that there have not been any advances in kneading block design in these intervening years. Three lobe eccentric kneading blocks for 2 lobe extruder systems were designed for more uniform energy input on the 2 lobe system, particularly in the melting zone [2]. As shown in Figure 2, the elements are offset so that 1 tip wipes the barrel wall while the other 2 have a significantly greater clearance (3 to 5 times) that permits polymer melt to flow more easily over these tips. This sets up a more circumferential rather than down channel material flow field within the element. The result is a more energy efficient as well as more homogeneous polymer melting [3]. The material exits the melting zone with few (if any) remaining un-melted particles. In addition to providing more uniform melting, 3 lobe kneading blocks are also less prone to compacting pigments, fillers or additives during the melting process [4].

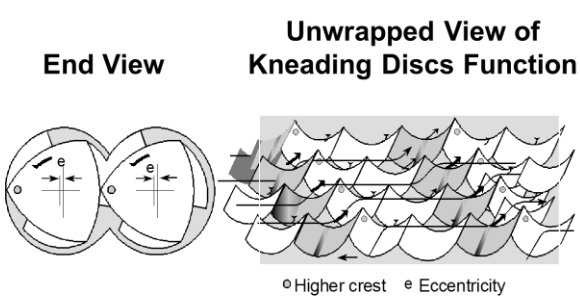

Figure 2: 3-lobe kneading block material flow.

The reduced thickness disc tip (SAM) kneading block [5] was designed for lower shear and material compression in the apex region. By removing a portion of the disc tip, there is less pressure generated at the apex.

Tapered kneading blocks [6] were also designed for reduced compression in the apex region, but specifically for elastomeric materials that dissipate significant amounts of heat energy with each compression cycle [7].

Reduced diameter reverse flight cross cut mixing elements (Compex) have been designed for mixing of high viscosity compounds such as wood fiber composites. The objective of these elements is to achieve low shear mixing by providing reduced shear stress over the flight tips and increased channel volume for longer residence time in the mixing zone [8].

During the intervening 60 plus years, basic performance characteristics for the kneading blocks have been defined. As illustrated in Figure 3, the key dimensions are: 1) disc width (W), and 2) disc stagger angle (S).

The first performance characteristic is related to the stagger angle (S) between successive kneading discs. As the stagger angle decreases, the cross-section of the opening between the discs is reduced. The result is material transport (T), i.e. down-channel flow, increases relative to material backflow (M). On the other hand, as S is increased, the open cross-section between the discs becomes larger. This reduces transport forces and thus the backflow portion of material flow increases. The result is an increase in distributive mixing (M).

The second performance characteristic is related to disc width. As disc width (W) is decreased stream splits per axial length are increased and so is distributive mixing. On the other hand, as the disc width is increased, there are fewer stream splits per axial length and therefore reduced distributive mixing. However, there is more opportunity for aggregates to be dispersed as the discs from the two shafts compress and accelerate material (Figure 4: Extensional Flow E) in the apex region. Figure 4 depicts a simulation in a progression of pictures of this higher axial velocity in the apex due to forces from discs upstream and downstream of the ones shown in the figure. In summary, as disc width decreases or stagger angle increases distributive mixing improves. Conversely as disc width increases the more dispersive mixing dominates.

Finally, another dimension, disc diameter, should be mentioned. Whether by design, i.e. three lobe elements for use in two lobe geometry systems (Figure 3), or simply the result of element wear, more material flows over the element crest as element disc diameter is reduced. One consequence is reduced conveying capacity due to more circumferential flow.

However, in spite of the above understanding of performance principles as well as the longevity of kneading blocks in the market, there is still a need for new developments of enhanced element geometry to keep pace with the overall advances in co-rotating twin-screw compounding equipment.

This paper will focus on the comparison of standard kneading blocks vs new involute kneading elements, specifically looking at some significant aspects related to performance.

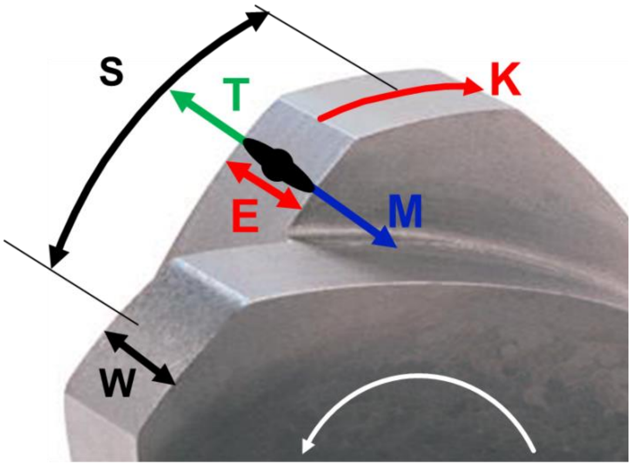

Figure 3: Kneading block key dimensions: stagger angle (W) and disc width (S). T indicates down-channel material transport, M represents back flow (distributive mixing) and E represents Extensional Flow (dispersive mixing) and K is the shear associated with any material that passes over the element crest.

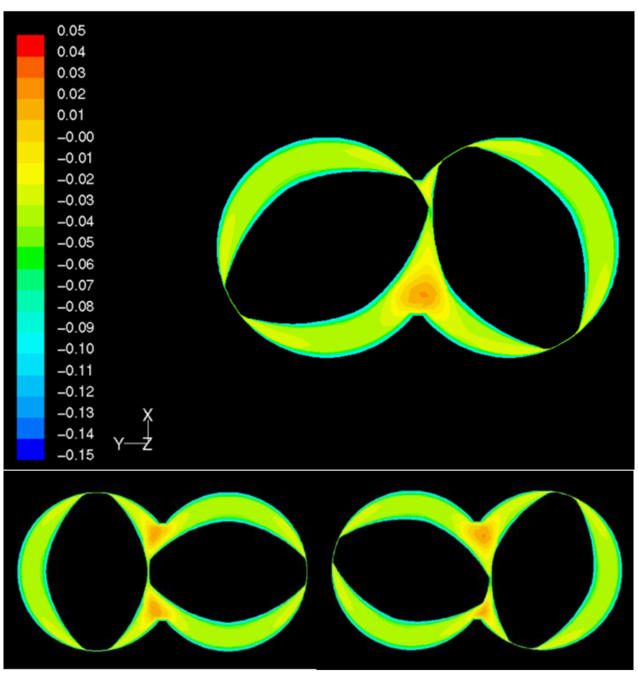

Figure 4: Simulation of axial velocity due to element rotation and material compression in the apex region.

Next Generation Element Geometry

To take advantage of increased torque and power transmission capacity introduced in the newest generation of twin-screw compounding extruders, solids feed conveying and melt/mixing capacity in, for example, some highly filled compounds, needed to be improved.

To help achieve this objective, a next generation family of screw and kneading block elements based on unique Involute derived cross section geometries have been designed, patented (Patent: EP 2 483 051 B1) and published in 2014.

The involute screw element concept provides enhanced flexibility for adjustment of shear and/or extensional flow on the material to be processed. Compared to the original Erdmenger profile, which is based on circles that result in a D_o/D_i profile, the Involute profile is not based on circles but more complex mathematical curves as described in the next paragraph and illustrated further on in the text.

The involute screw element has an outer contour with at least one outer contour portion, the associated evolute of which is a quantity of at least three points, each of the points lying outside the longitudinal axis and within the outer radius of the treatment element and two respective adjacent points having a spacing from one another, which is less than half the core radius. The treatment element ensures high flexibility during the adjustment of shear and/or extensional flows on the material to be treated [9].

As an illustration of the above text, on the right side of Figure 5, a line/stick with the length of the elements centerline distance is tangent to a circle but with no fixed contact point. As a result the contour of the involute elements is composed of circular arcs in cross-section. However as is illustrated in the left side of Figure 5 major key characteristics, such as self-wiping, are still achieved.

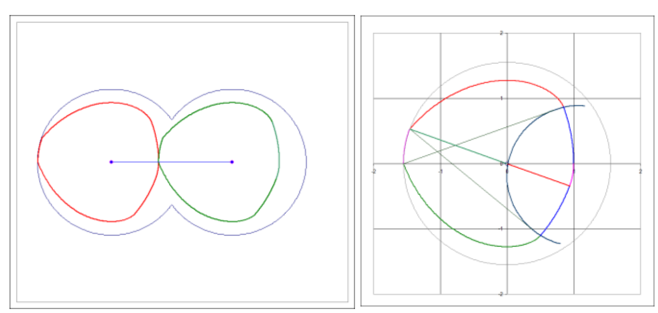

Figure 5: Schematic of new element construction geometry

In figure 6 a single flite design Erdmenger geometry (left side) is compared with an involute screw design which is obviously also single-flited, but the treatment of the materials by the two geometries will be different. The crest that wipes the barrel wall for the Erdmenger design (left) has a sharp entry angle and constant gap clearance. The Involute profile (right), generated by the rotation of the centerline length "rod" from the first contact point (far right), to the second (middle) and then the third (left), has a tapered entrance angle to enhance material flow into the highest shear regions. The result is that the Involute element has significantly greater dispersive mixing potential.

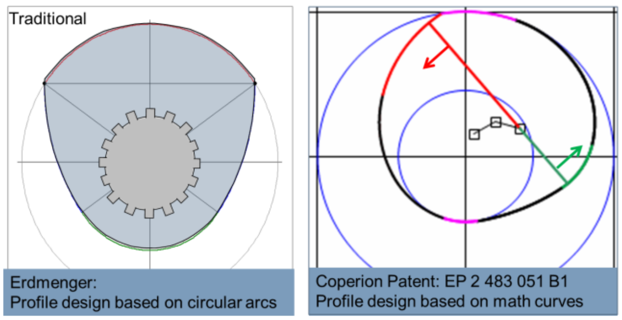

Figure 6: Traditional single flight Erdmenger design vs. and Involute single flight geometry. The Involute element is generated by the rotation of the centerline length red-green "rod" from the first contact point (far right), to the second (middle) and then the third (left)

As a consequence of Involute design flexibility, previous disadvantages such as high pressure peaks in the intermeshing zone can be also be mitigated, Figure 7. The highest pressure peaks occur during the tip interaction of the two screw elements, the so called intermeshing area or APEX. This can lead to an agglomeration of solids that subsequently have to be dispersed. These can include mineral fillers, pigments, or any other solid particle.

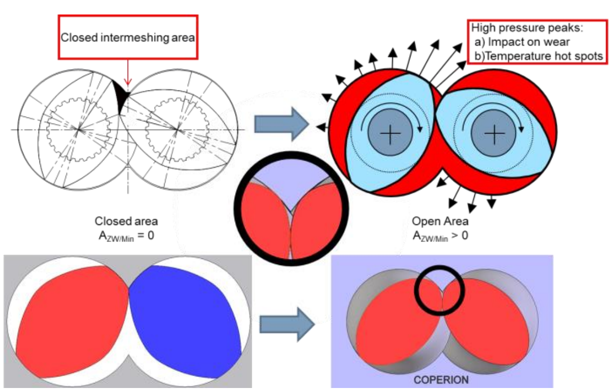

Fig. 7: Reduced pressure peaks in the APEX.

Simultaneously, as APEX pressure is reduced, radial forces are also lowered in the non-closed intermeshing zone. Therefore, just as with reduced force on sandpaper, wear can be reduced. Additionally, the new involute screw design has several application advantages which are still not all investigated.

Experimental & Results

A series of screw configuration designs was evaluated using a ZSK 58 Mc[18]. Different screw configurations have been tested using traditional "standard" screw element configurations vs. configurations incorporating Involute elements to improve the output rate and quality.

Figure 8 illustrates the typical process set-up for compounding of PP/PE with up to 70% by weight $CaCO_3$. Polymer plus additives are fed into barrel 1 and melted in barrel 2/3. For highest rates, a small amount of additional filler can be fed into barrel 1. The main portion of filler is fed via the lateral side-feeder into the melt and finally incorporated downstream in barrel 5/6 as well as barrel 8. Barrel 7 is used to remove the entrapped air of the filler.

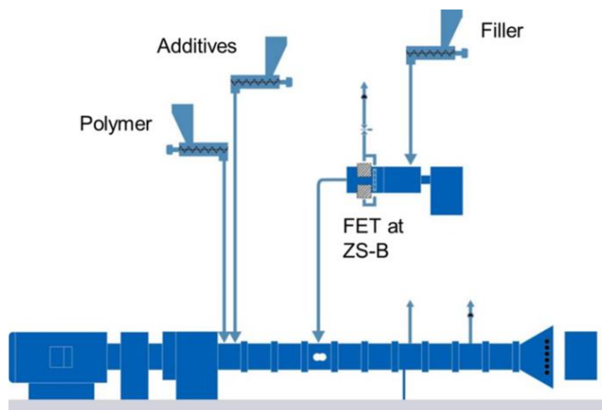

Figure 8: Process set-up for PP/PE + 70% $CaCO_3$

The maximum throughput with a standard screw element configuration was up to 550 kg/h. With the new involute screw elements in the melting/mixing zones, the rate was significantly increased up to 900 kg/h as the filler could be incorporated under more stable operating conditions into the polymer, see Figure 9.

ZSK58Mc[18]

Recipe No.	Recipe	Max. Rate Standard-Screw profile	Max. Rate New Screw profile (Involute)	Rate increase
4	PP MI 8 + 70% CaCO3	550 kg/h	900 kg/h	+60 %

Fig.9: Comparison of throughput

Subsequently different recipes have been investigated on a lab unit (ZSK40McPlus) to determine the benefit in terms of throughput rate as well as quality.

Figure 10 summarizes some major results investigated on this test machine. The machine set-up was comparable to the set-up shown in Figure 7. The data show that depending on the filler and viscosity of the polymer, the throughput can be increased over 100% as the former process limitation of incorporation of the filler into the polymer matrix was eliminated. Other limitations such as material back up in the side feeder or in combi-block barrel were significantly reduced. This opened the operation window for the process. In general, all formulations for film applications, i.e. breathable film or even automotive PP grades could have been optimized in terms of throughput rate and process window.

Formulation	Max. Rate Standard-Screw profile (kg/h)	Max. Rate New Screw profile (Involute) (kg/h)	Increase [%]
PP + 55 % Talc	180	220	+ 22%
PP + 70% $CaCO_3$	180	250	+ 38%
LLDPE (MI 20) + 28% TiO2 + 42% CaCO3	110	290	+ 160%
PP (MI 12) + 70% CaCO3	130	300	+ 125%
PP (MI 12&70) + 75% Talc	100	200	+ 100%

Figure 10: Comparison of throughput on a ZSK40McPlus

While not specifically shown in the data presented, the Involute elements have enabled the utilization of higher available torque and therefore the high-torque machine can be used more efficiently. This also can be seen as the rate was increased while the rpm was held constant. The result was that specific energy input SEI (kWh/kg) was reduced. This resulted in an average temperature decrease of 10 – 20 degrees C for filled and highly filled polymers. With respect to product quality (dispersion), for most recipes the filter pressure value (FPV) as an indication of dispersion was significantly reduced. For illustration, Fig. 11 shows the amount of defects or undispersed particles in a PE film. Using involute screw elements resulted in the best quality at highest throughput rate.

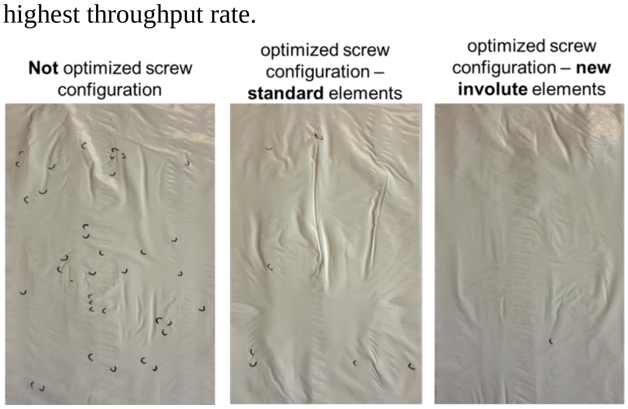

Fig.11: Filler dispersion in PE film

Scale-up to larger lines was demonstrated and approved also, as shown for example on a ZSK92Mc[18]. The throughput rate was increased by 36% by using involute screw elements. The specific energy input SEI was reduced down to 0.064 kWh/kg for 3000 kg/h with a filler content of $CaCO_3$ of 80%wt.

Summary

Involute screw elements have been shown to provide several advantages for processing highly-filled recipes (70-85% $CaCO_3$, TiO_2, mainly based on PP/PE as well as 20-50% talc for automotive grades) for which the dispersion rating and the incorporation of the filler represents a limitation. Besides the obvious higher throughput rates, these involute screw elements have demonstrated higher loading of filler, better dispersion and homogenization, lower energy consumption (SEI in kWh/kg) and a significant increase in profitability.

Comprehensive tests have shown a remarkable throughput increase depending on the recipe. For example, when processing PP and 70% C aCO_3 on a twin screw extruder ZSK58Mc[18] the new screw elements achieved a significant throughput increase from 550 kg/h to 900 kg/h. Similar results have been reached when processing PE with 80% $CaCO_3$ on a ZSK92Mc[18]. In this case throughput was increased from 2,200 kg/h to 3,000 kg/h.

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Key Words: Twin-screw, compounder, kneading blocks, Involute Screw Elements