FUNDAMENTALS OF TWIN-SCREW COMPOUNDING: KNEADING BLOCK PERFORMANCE CHARACTERISTICS

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Abstract

The co-rotating fully intermeshing twin-screw extruder has evolved significantly in the 60 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 a rather significant number of advancements have been introduced during the intervening years. Even today 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 were filed in the late 1940's and early 1950's. In spite of their longevity in the market, there are still unknown qualitative as well as quantitative operational characteristics. This paper will focus on kneading blocks, specifically looking at some significant aspects related to performance. These include pressure generation as a function of 1) absolute pressure, 2) disc profile (2-lobe vs 3-lobe), 3) disc width, 4) disc stagger angle, and 5) material viscosity.

Introduction

The co-rotating fully intermeshing twin-screw extruder has evolved significantly in the 60 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 a rather significant number of advancements have been introduced during the intervening years. Even today 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.

Conveying element and kneading block design, while acknowledged as the work horses for material conveying, particle distribution and aggregate dispersion in screw configurations, 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.

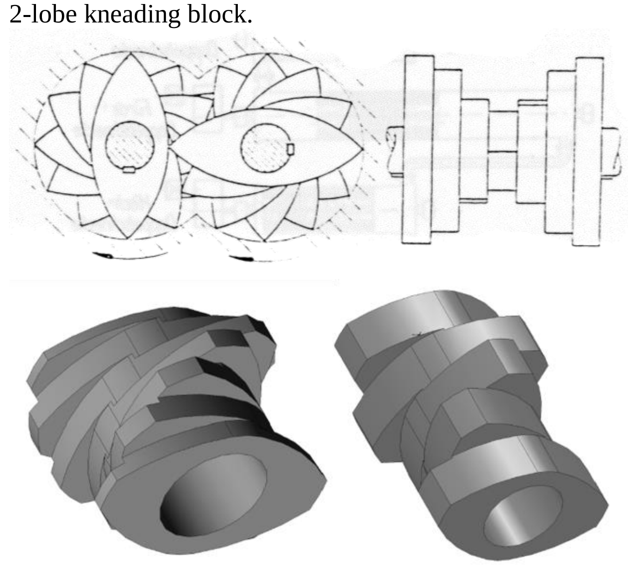

Figure 1: Comparison of original kneading block design (top) vs. the current standard kneading block (below).

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 [1]. As shown in Figure 8, 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 more easily flow over these tips. This sets up a more circumferential rather than down channel material flow in the element. The result is a more energy efficient as well as more homogeneous polymer melting [2]. 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 also are less prone to compacting pigments, fillers or additives during the melting process [3].

The reduced thickness disc tip (SAM) kneading block [4] 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 [5] 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 [6].

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 [7].

During the intervening years, basic performance characteristics have been defined. As illustrated in Figure 2, the key dimensions are: 1) disc width (W), and 2) stagger angle (S). The first performance characteristic is related to the stagger angle (S). As S is decreased, downstream material transport (T), or flow, increases relative to the backflow portion (M) of material flow since the cross-section of the opening between the discs is reduced. 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 can increase. The result is an increase in distributive mixing (M).

The second performance characteristic is related to disc width. As disc width (W) 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 2: Extensional Flow E) in the apex region. Figure 3 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. On the other hand, as the disc width is decreased stream splits per axial length are increased and so is distributive mixing. 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 8), 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 are still unknown qualitative as well as quantitative operational characteristics for kneading blocks.

This paper will focus on kneading blocks, specifically looking at some significant aspects related to performance. These include pressure generation as a function of absolute pressure, disc profile (2-lobe vs, 3-lobe), disc width, stagger angle, and material viscosity.

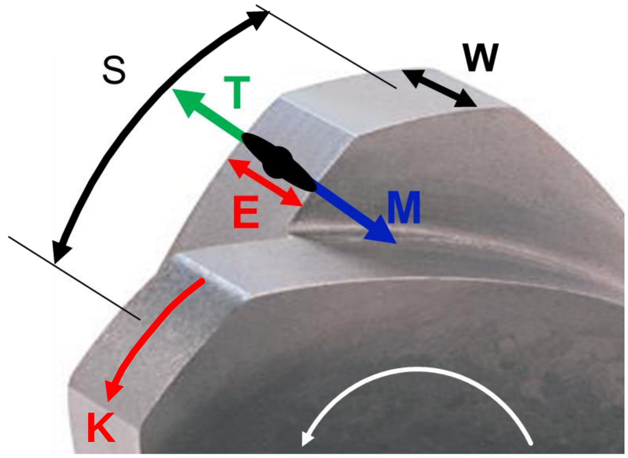

Figure 2: Kneading block key dimensions: stagger angle (W) and disc width (S). T indicates down-channel material transport, M represents back flow (distributive mixing) and E represents Extensional Flow (dispersive mixing) and K is the shear associated with any material that passes over the element crest.

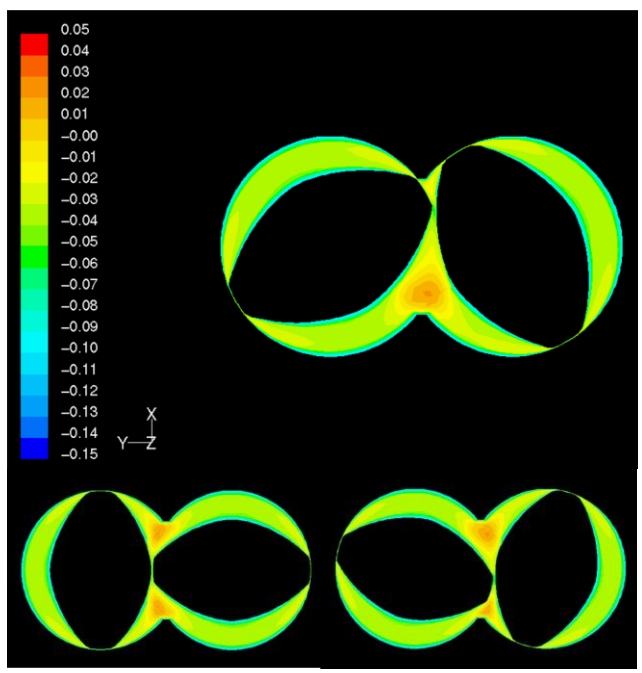

Figure 3: Simulation of axial velocity due to element rotation and material compression in the apex region.

Experimental

A series of screw configuration designs was evaluated using a ZSK 58 Mega Compounder to determine the pressure build up or pressure drop characteristics of kneading blocks along a specific length of barrel. The pressure was measured at three locations by a sequence of three Dynisco pressure transducers as illustrated in Figure 4. The distances between the first and second transducer was 165 mm, and 45 mm between the second and third.

The KB element series evaluated consisted of both 2-lobe and 3-lobe geometry. The 2-lobe KB series were 180 mm. They consisted of ½ or 1 diameter (with respect to machine diameter) long 5 disc forwarding kneading blocks (KB45/5/30, KB45/5/60), ½ or 1 diameter 5 disc neutral kneading blocks (KB90/5/30, KB90/5/60). The 3-lobe series each had a 2/3 diameter 5 disc 2-lobe to 3-lobe transition kneading block (KB45/5/40 2L-3L) at the entrance and a similar transition at the discharge. In between the transition elements were three KB45/5/40 3L kneading blocks in one series, and two KB45/3/50 3L kneading blocks in the other series. The series were all single element type geometry as shown by a representative example in Figure 4. Additionally, each of the KB series was completed with a conveying element or restrictive element. The restrictive elements ranged from a ½ diameter reverse flow kneading block (KB45/5/30LH) to narrow pitch reverse pitch single flited elements (15/45SFLH).

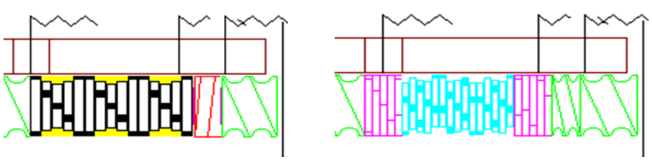

Figure 4: Examples of KB series with restrictive and conveying end elements.

In addition to utilization of various restrictive element geometries, a radial throttle was installed in the barrel section directly above the restrictive element. This permitted the reduction of pressure drop across the restrictive elements on a real time basis.

Two PE grades were used during the testing. The first was a Fortiflex 5 MI HDPE and the second 2 MI DuPont DPE-20 LDPE. Due to limited supply of raw material the 5 MI HDPE was run with the 3-lobe KB series and the 2 MI LDPE with the 2-lobe series.

The operating conditions unless otherwise note were 300 rpm screw speed and 175 Kg/hr.

Results

The first set of results is shown in Figure 5 for the ½, and 1 diameter forwarding and neutral kneading blocks. Each of these configurations was restricted by the 15/30 LHSF element. The material processed was DuPont Type DPE 20 LDPE.

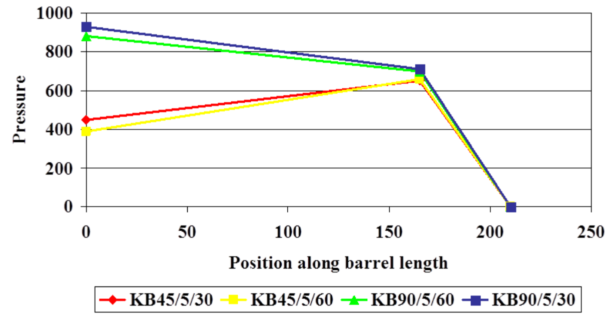

Figure 5: Effect of disc width and stagger angle on pressure build up and pressure drop characteristics.

As expected, the forwarding kneading blocks (KB45/…) exhibited a pressure rise upstream of the restrictive elements while the neutral kneading blocks (KB90/…) had a pressure drop. The unexpected result is that the 1 D conveying kneading block series had a greater pressure increase (albeit minimal) and the 1 D neutral kneading block series had a smaller pressure drop when compared to the corresponding ½ diameter series equivalents.

Based on practical experience it is customarily acknowledged that a tighter pitch conveying element is more efficient than a wider pitch element at generating pressure to overcome a flow restriction, whether it be a dynamic (restrictive element) or static (die) restriction. Based on this supposition, one would suppose that the kneading block with the tighter (smaller) conveying element pitch equivalent would be more effective. However, it appears that other forces are dominant. It could be that the axial material velocity generated as the wider kneading discs compress material in the apex region is more important than the forward flow generated by the helical geometry of the staggered discs (Figure 3).

Figure 6 indicates that pressure build up efficiency for wider disc (KB45/5/60) forwarding kneading blocks relative to narrow disc kneading blocks is seemingly independent of restrictive pressure. To illustrate this point the radial throttle mechanism was opened to 2 mm. At both high and low restrictive pressures the wider disc KB series exhibited a greater dP/dL than the narrow disc KB.

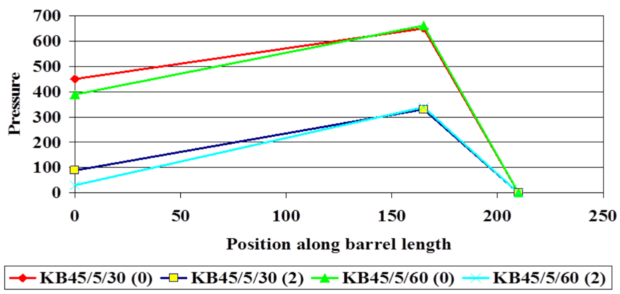

Figure 6: Impact of restrictive pressure on pressure build up efficiency of forwarding elements with respect to disc width.

Figure 7 shows another interesting result. The radial throttle mechanism was sequentially opened to a 1 mm, 1.5 mm and 2 mm gap. The result, as expected was an initial large reduction in restrictive pressure, followed by smaller reductions. The more interesting observation is that the delta in pressure along the length of the ½ diameter forwarding KB series remained constant.

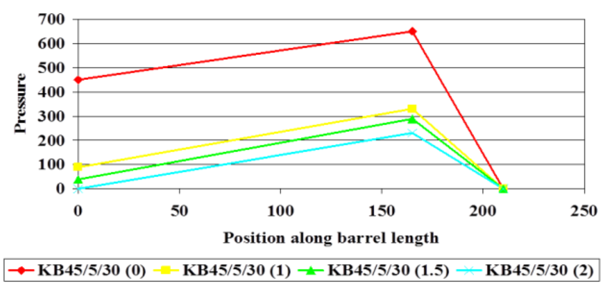

Figure 7: Impact of restrictive pressure value on pressure build up efficiency in 2 lobe kneading blocks.

The same types of experiments were performed on series of 3-lobe kneading blocks. It is generally acknowledged that 45 degree stagger 3-lobe kneading blocks, do forward material but are not very efficient. Because of the non-wall wiping clearances of 2 out of three discs, there is a tendency for more circumferential flow than down-channel flow, Figure 8. Therefore at higher rate/rpm (Q/n) they act as restrictive elements.

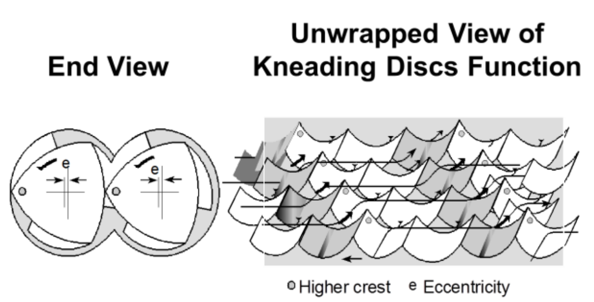

Figure 8: 3-lobe kneading block material flow.

Two series of 3-lobe kneading blocks were evaluated as described previously in the Experimental section. The first was the standard eccentric 2/3 D elements (KB45/5/40 3L). The second were wider eccentric disc elements, KB 45/3/50 3L.

As a partial aside to reviewing the pressure rise or drop across the series of elements, Figure 9 shows the results for absolute back up pressure for the various restrictive elements incorporated into the experimental runs. The material, as noted in the Experimental section, was the lower viscosity 5 MI HDPE. Four of the restrictive elements (30/30, 15/15 LHSF, 15/30 LHSF and 15/45 LHSF) are not typically used in commercial applications. The 30/30 is a conveying element and only acts as a restrictive device if the throughput rate is greater than the conveying capacity. Somewhat like the back up at the toll booth at rush hour. All the traffic is moving forward but the volume is more than the human toll takers or electronic recording devices can handle. The LHSF are extremely restrictive and would back up material beyond the start of most typical kneading block sections.

The standard restrictive elements (LHKB and LH screw bushing) generated a back pressure that was just a little less and a little more than 100 psi respectively for this material at the 300 rpm and 175 Kg/hr. The 30/30 element provided no back pressure at these operating conditions.

The dP/dL data shown in Figure 9 was generated by the wide disc 3-lobe kneading block geometry.

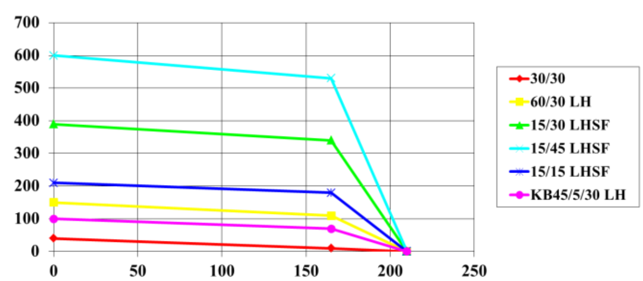

Figure 9: Pressure generation characteristics for a wide range of element geometries

Figures 10 shows the pressure drop across the standard vs. wide disc 3-lobe kneading blocks for a series of restrictive values generated by elements as well as throttle valve settings (indicated by the parenthetical value 5 (i.e. 5 mm clearance)). This list includes some inherently forwarding elements (30/30). Unlike the 2-lobe elements, there does not appear to be a clear indication of significant difference between the efficacies of the wide vs. the narrower disc elements. One possible explanation is that the wider disc kneading block section was 20 mm shorter at 100 mm than the narrower series at 120 mm. Another impact might have been the narrow disc transition elements on the inlet and outlet of the series. However, at the lower restrictive pressure there is a small differential in upstream pressure, but for the most restrictive configuration (15/30 LHSF) there is no difference in initial pressure. Finally, as previously seen in the 2-lobe geometry series the results indicate that the dP/dL drop is the independent of restrictive pressure value.

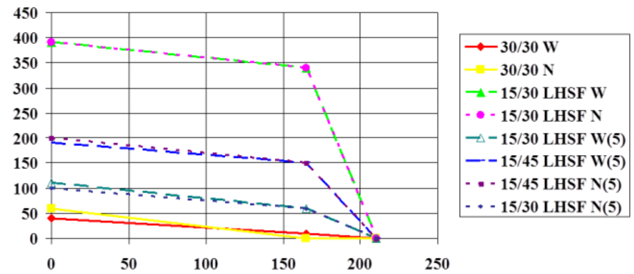

Figure 10: Pressure drop comparison across wide and narrow disc width 3-lobe kneading blocks.

All previous data were recorded at 300 rpm. Figure 11 displays data for narrow disc 3-lobe kneading blocks across a range of rpm values. The KB series is backed up by a 30 mm pitch, 30 mm long conveying element. The data shows that, as expected, rpm has a significant impact on the restrictive intensity of the 30/30 element. Above 150 rpm the element is non-restrictive. Interestingly, the lower the rpm, the greater the dP/dL becomes across the elements. Additionally while not incorporated into this slide, this relationship is also true for the wide 3-lobe kneading disc elements.

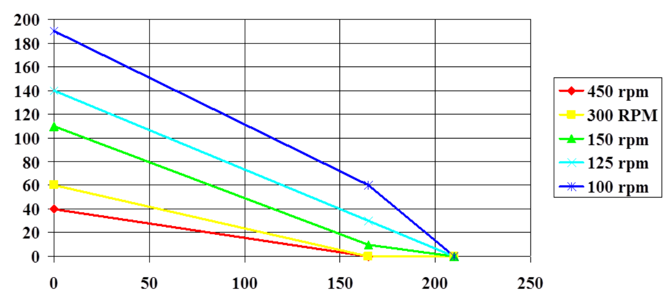

Figure 11: dP/dL as a function of rpm for narrow 3-lobe KB series with a 30/30 conveying element at the end.

It was mentioned in the Experimental section that two types of PE, each with a different MI were used during the experimental runs. The objective was to gain a general understanding of the impact material type, as well as MI, may have on overall pressure drop and dP/dL. A comparison was made using the same screw configuration and operating conditions. Figure 12 depicts the results from the narrow 3-lobe KB series with a 15/45 LHSF screw bushing as the backpressure generation. There was a nominal 500 psi difference at the "0" position pressure transducer between the 2 MI and 5 MI material with a zero clearance throttle setting. The nominal pressure difference when the throttle was set at 2 mm clearance was significantly less, 150 psi. The zero position pressure difference between zero throttle clearance and 2 mm clearance was significantly greater for the 2 MI material (1020 psi to 350 psi) than the 5 MI PE (550 psi to 200 psi). However the relative % pressure drop was approximately the same. It should also be mentioned that the open discharge temperature was significantly different between the 2 MI (273 C) and the 5 MI (228 C) materials. The temperature difference between the zero and 2 mm clearance throttle settings was 8 C and 4 C respectively. Finally, while not statistically significant, the dP/dL drop across the 3-lobe elements was greater for the 2 MI material than the 5 MI PE.

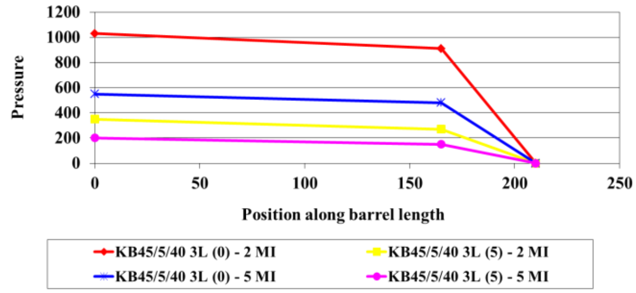

Figure 12: Impact of material Melt Index on pressure drop and dP/dL

Summary

The results from these experimental runs confirm many general understandings with respect to kneading block performance, such as the "passive" conveying nature of 3 lobe kneading blocks. On the other hand some new insites were noted such as the better dP/dL performance for wide disc kneading blocks vs. narrow disc kneading blocks with the same stagger angle.

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