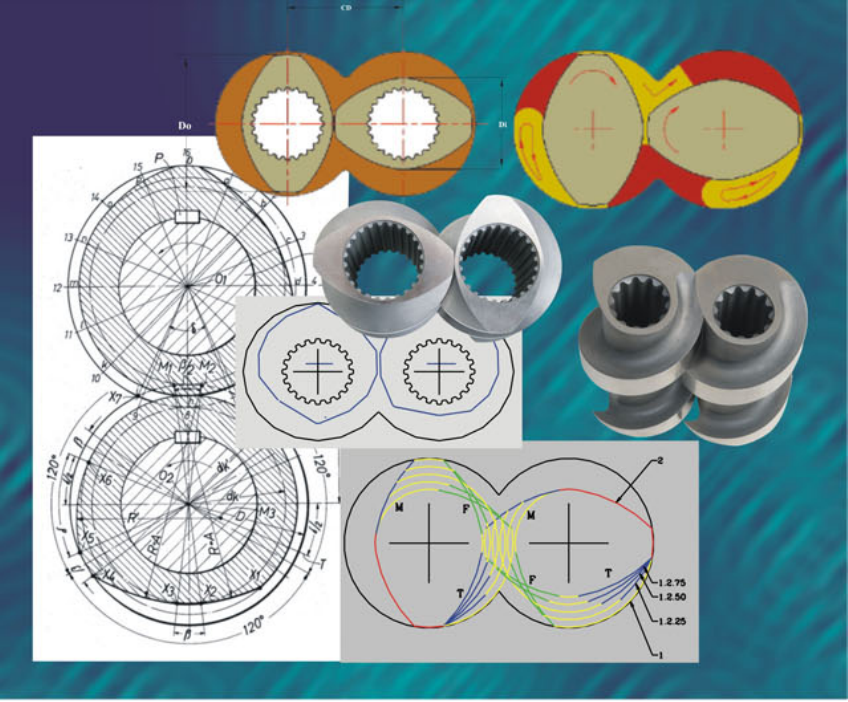

GEOMETRY Unraveled

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GEOMETRY Unraveled

A Technology Update on Twin-screw Extrusion

by

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Introduction

Co-rotating Twin-screw extruders are versatile devices that allow work to be done efficiently on plastic materials. The work done generally raises the temperature of the material being processed, resulting in a partial or complete fusion of the mixture, an increase in the uniformity of the composition, a chemical union between the components constituting the mixture and finally a reduction in the size of particles in that mixture. Work done on the material is the result of application of shear forces, extensional forces that cause elongation or stretching of material, compressive forces that results in pressure build-up and squeezing of the material and bending forces that causes fibers and layers to fold and interact. These forces occur in three dimensional space inside the extruder defined by the Axial Plane, Longitudinal plane for each screw and several Radial planes. Flow of material between elements in different radial planes creates lateral shear in the material. In general, radial and lateral shear rates are 10 to 100 times greater in magnitude compared to axial or longitudinal shear stress.

Radial and Lateral shear are not experienced uniformly by every macro-molecule or particle in the mix leading to the most common difficulty in plastics processing. Improvements in the working of the extruder always lead to creating circumstances for uniformity in the radial and lateral shear rates, extensional flow patterns and frequent re-orientation.

Any effort to fully understand the working of a twin-screw extruder has to begin with a study of the geometry of the twin-screw equipment. In 1978, Booy [1] conducted such a study based on about 20 years of work carried out in the field. Since then, important innovations such as Eccentric Elements and Fractional Lobed Elements have revolutionized the effectiveness of the equipment.

This paper attempts to provide a most recent update on the geometry of the elements, the crucial part of the processing section in a co-rotating twin-screw extruder.

Technology Update on Twin-screw Extrusion: Geometry Unraveled

Known Element Geometry

The essential requirement of a closely intermeshing co-rotating twin-screw extruder element profile is the ability for one screw to wipe the other and vice-versa. The Barrel[1] Diameter (D_b) and Center-distance (Cd) are the fundamental parameters used to define the geometry of the element. The conveying screws, kneading blocks, mixing elements and other elements are formed by the helical or linear transformation of the cross-sectional geometry of the profile.

32.00
Center Distance

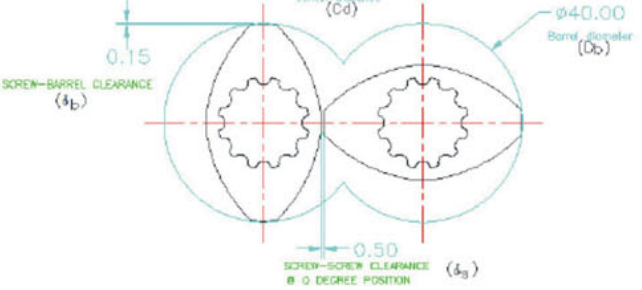

Figure 1: Cross-section of a Barrel with Element

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[1] Barrels are also referred as Cylinders or Housing

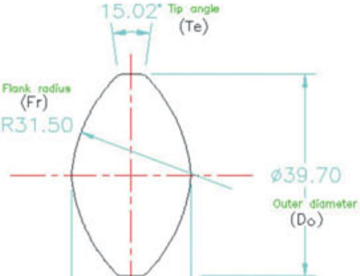
The relationship between the screw profile parameters and the barrel parameters can be written in the following manner

Barrel Diameter (D_b) = Outer Diameter (D_o) + 2 * Barrel-Screw Clearance (δ_b)
Center Distance (Cd) = {Outer Diameter (D_o) + Minor Diameter (D_i)}/2 + Screw-Screw Clearance (δ_s)

The ratio of the Outer Diameter (D_o) and the Minor Diameter (D_i) is called the Ratio of Diameters (Rd) or the D_o/D_i ratio.

Ratio of Diameters (Rd)	Number of Lobes (Nl)
1.000 <Rd <1.180	1,2,3,4
1.180 <Rd <1.366	1,2,3
1.370 <Rd <2.414	1,2
2.420 <Rd < ∞	1

For a ratio of 1.50, it can be seen from this table that it is not possible to design a tri-lobed (three lobes) profile. Presently, most twin-screw extruders are designed with ratio of 1.50 and above. Therefore, the bi-lobed[2] (two lobes) geometry is the most commonly used.



Ø23.30
Minor diameter
(Di)

Figure 2: Outer Profile Parameters

The Tip Angle (Te) can be expressed in the following equation
Tip Angle (Te) (in Radians) = 3.1415 (Pi) / Number of Lobes (Nl) – 2 * $\text{Cos}^{-1}(\text{Fr}/D_o)$ Where
Flank Radius (Fr) $= (D_o + D_i) / 2$

The Tip Angle obtained using the above equation is called "Erdmenger" or "Constant-clearance" Tip Angle (Te).
For a given Ratio of Diameters (Rd), a twin-screw geometry with a larger Tip Angle than Erdmenger Tip Angle (Te) is not possible.

---

[2] Single lobed profile is possible for any ratio. However, higher number of lobes results in increased free volume.

When the Number of lobes (Nl) is an odd number (1 or 3), then the two profiles form a conjugate pair in the same orientation or at an angle of 0 degrees with respect to the other. When the Number of lobes (2 or 4) is an even number the two profiles form a conjugate pair at a defined angle (90 degrees or 45 degrees) respectively.

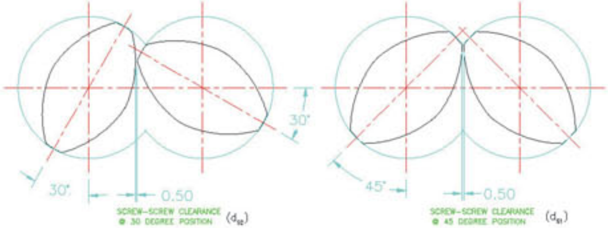


Figure 3: Bi-lobes forming Conjugate pair (with constant clearance) at 90 degrees relative to the other.

The clearances play an important role in ensuring that the screw profile can center itself inside the barrel at the time of processing. Smaller or larger clearances can be used while processing different type of material.

Typical Clearance between the Screw and the Barrel (δ_b) = 0.25mm
Typical Clearance between the two Screws (δ_s) = 0.5mm
For a constant clearance profile $\delta_s = \delta_{s1} = \delta_{s2}$; clearances at all rotational position is constant.

Due to certain processing requirements (or manufacturing convenience), the Actual Tip Angle (Ta) used may be smaller than the Erdmenger Tip Angle (Te). This modification changes the clearance when the profile rotates to a new position.

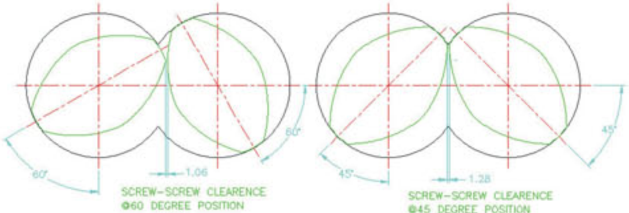


Figure 4: Bi-lobes forming Conjugate pair with varying clearances

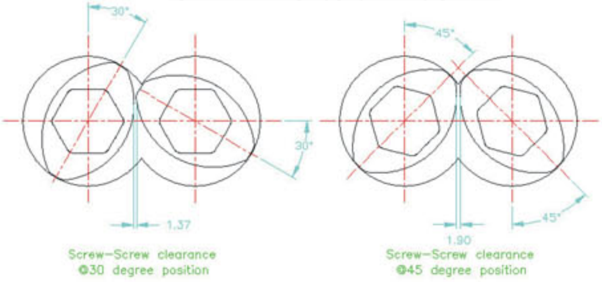


Figure 5: Bi-lobed Single-arc profile forming a Conjugate pair

It is possible to design the geometry using a single arc. Such geometry result in a varying clearance. Interestingly, the highest clearance although at the 45 degree position is not at the tip but a little below it. This results in a reduction of wear at the tip.

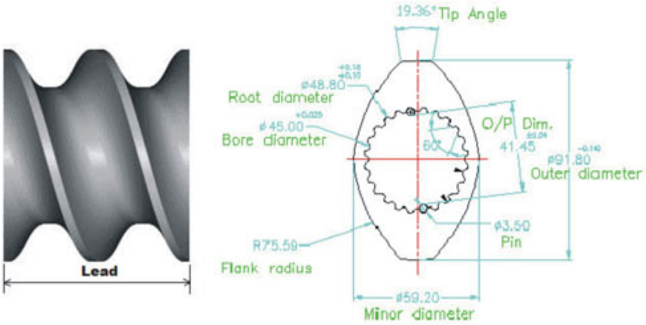


Figure 6: Conveying Screw Element

The screw element is obtained by a helical transformation. This transformation is defined by a continuous rotation with a forward movement (translation) along the axis of rotation. While looking at the screw element such that the rotation is in a clockwise direction, if the translation is downward then the screw is called a Right Handed Screw element. For a clockwise rotation, if the translation is upward, then the screw is called a Left Handed Screw element. The Lead of the screw element is defined as the translation length for a complete turn (360 degrees).

The important Conveying screw element parameters are therefore the Lead (Ld), Hand (Hd) and Length (Ln). When very long lead elements where the lead is 10D or more are used in right and left lead combination, the formation looks similar to a Farrel type continuous mixer element.

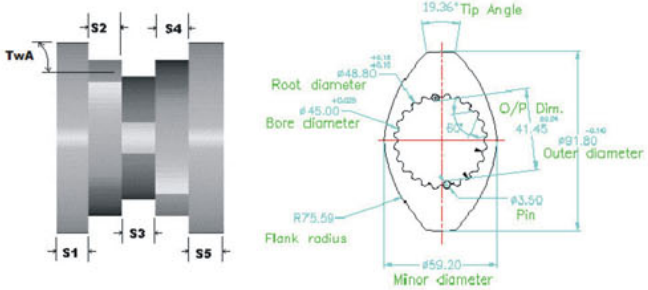


Figure 7: Kneading Element

The Kneading Elements are formed by translation of the profile by a distance called the Segment Thickness. The next segment is started at a new twist angle and taken through another translation. There is usually an overlap between the adjacent segments resulting in a clearance between the segments.

The important Kneading Element parameters are the Length (Ln), Twist Angle (TwA), Hand (Hd) and Segment Thickness (Sn) and Clearances (Cn).

Eccentric Element Geometry

In 1989, Häring et al.[3] introduced a new concept in Element Design. They discovered that the profile can be designed for a smaller diameter ratio (Rd) for a given same center distance and moved eccentric to the shaft. This enables tri-lobed profile to be designed for diameter ratios as high as 1.5 or more.

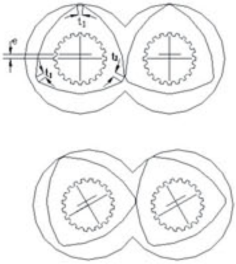


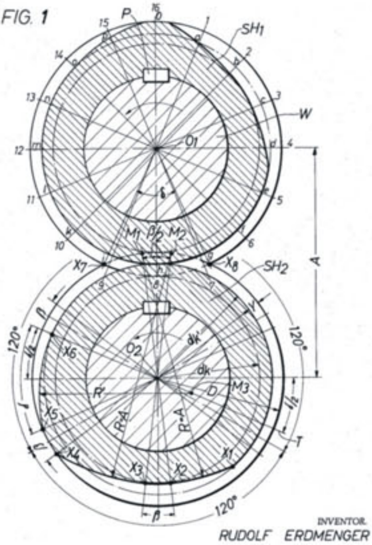
Figure 8: 3 Lobed Eccentric elements with Do/Di = 1.

It may be noted that concentric tri-lobed elements cannot be used in a bi-lobed extruder with Do/Di greater than 1.37. Eccentric lobes used as in the form of conveying screws are sometimes referred to as camel-back elements. Otherwise, eccentric lobed elements are used as kneading blocks. An advantage in using eccentric lobed elements is that it reduces some of the non-uniformity in lateral shear. It all leads to more frequent reorientation causing improvement in mixing action.

Fractional Lobes

In 1963, Erdmenger [6] wrote in a relatively less known Patent document, "one disadvantage that was hitherto encountered in apparatuses of this type was that it was only possible to vary the dimensions lying in the axial direction but not the dimension lying transversely to the axis, e.g. the thickness of the layer of material used, which often has an important effect on the transfer of heat or the transfer of material or the course of the reaction". Tri-lobed profile was modified in a new manner in this invention – a predecessor to the Fractional lobed elements. Erdmenger calls this as the most important alteration in practice. This design is an instance of fractional lobed element but only half of it. It should be designated under the fractional lobe naming convention as the 1.3.50B/2.

FIG. 1



Sakagami [4] recognized that Element profile can be created by applying different Diameter Ratios from lobe to lobe. In the case of the example shown below [R#], one of the bi-lobe has the standard ratio, while the other one has a decreased ratio resulting in an increased Inner Diameter (Di) and decreased Outer Diameter (Do) which is clearly evident in the figure. Sakagami calls this SMAP screw design and believes that kneading blocks can be completely eliminated for melting with this design. A screw elements formed with this design resembles a barrier screw in a single screw extruder.

Figure 9: Erdmenger's half a Fractional Lobed Element Design

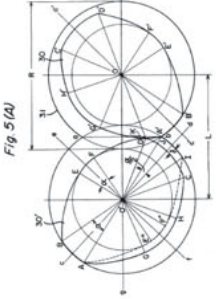


Figure 10: Sakagami Modification resulting in a complete fractional lobed element 1.2.66

Fractional Lobe Geometry takes this approach to any number of lobes with a unified concept. Fractional lobes are formed using two different Integer lobes together. At this time, there is only one condition to be met that the ratio of the two such lobes should also be an integer. Therefore a Single flight profile (Uni-lobe) and a Bi-lobe can form fractional lobes such as 1.2.xx where xx can be number from 01 to 99. These numbers 01 to 99 will define whether the fractional lobe will look more like a single flight element or a bi-lobed element. A Single flight profile and a Four-lobe profile can form fractional lobes such as 1.4.50 etc. 1 and 3 lobes can also be combined as well as 2 and 4 lobed. These combinations result in an infinite series of profiles to chose from offering enormous capability in the hands of extruder users and designers.

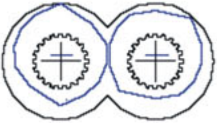


Figure 11a: Fractional Lobed Geometry 1.4.50

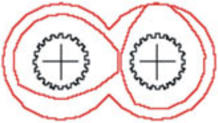


Figure 11b: Fractional Lobed Geometry 1.2.50p

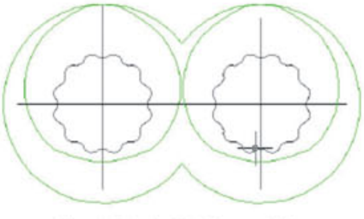


Figure 11c: Fractional Lobed Geometry 1.3.80a

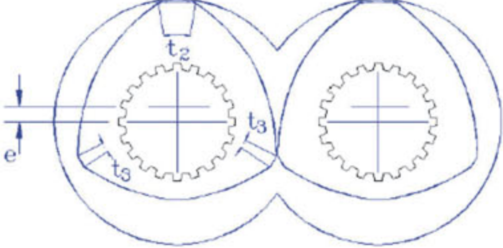


Figure 12: Fractional Lobed Geometry 1.3.80b

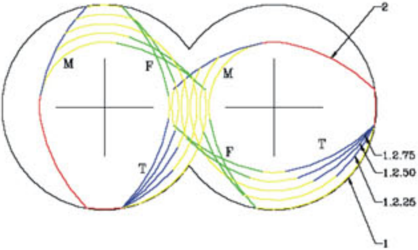


Figure 13: Mathematical Principle for generation Fractional Lobes

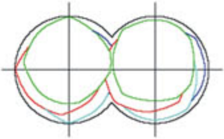


Figure 14: Kneading Disks formed for 1.4.50 Fractional Lobes

Other Modifications

SK modification

Direction of Conveying
Tip angle
17.60°

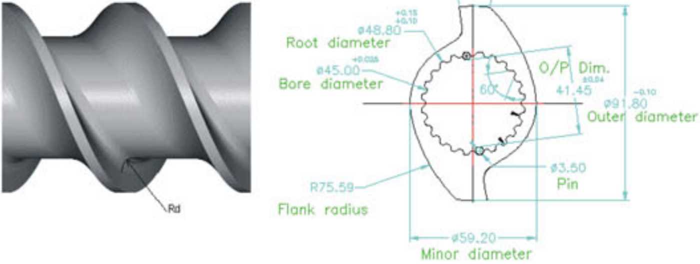


Figure 15: Under-cut Element

This element is used to enhance the free volume during intake or venting. The axial cross-section is modified to become perpendicular to the axis with a small radius (Rd) at the minor diameter.

It is important to note these elements are only partially wiping and not fully wiping the other element. These elements are generally used in the intake zone before the solid material forms a melt. However, they can be used in any zone that is partially filled after melting. This is because the flow of material can itself create the effect of cleaning. Importantly, wiping profiles does not always clean, since cleaning action requires transfer of material forward during the act. If material is pushed backwards or in a radial direction, cleaning does not Occur.

FV modification (Patent Pending)

These are specially modified highly efficient conveying elements. The elements can convey (by ploughing into the material with a shovel like surface) slippery and other difficult to convey materials at high rates compared to any of the available element geometry.

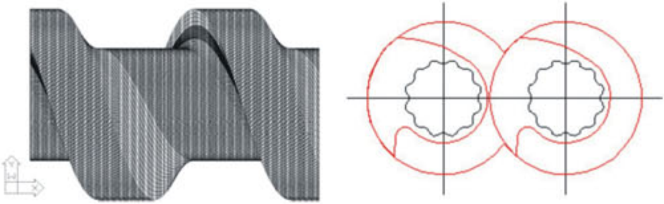


Figure 16: SFV element for Intake Zone

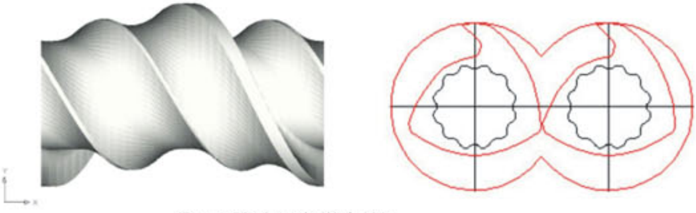


Figure 17: TFV element for Side-feed Zone

These elements have the ability to feed low bulk density material (such as a 50% Talc pre-mix) at an extremely high rate (around 2 to 4 times the capacity of a SK type element in starve feed mode).

These elements are capable of turning a feed-limited extruder (as in the case of applications with low bulk density material) to that of a torque limited one (as in the case of most applications). The geometry has a special nature of improving the feed-rate at greater speeds unlike standard elements which tend to fluidize the material and a drop in feed-rate occurs at higher speeds.

Several other modifications including screw mixing elements such as SMEs, ZMEs, TMEs have been left out from this discussion. These grooved modifications sacrifice on self-cleaning either by wiping or due to natural flow and were a quick-fix remedy rather than a lasting solution to certain distributive mixing needs. In general, these elements are slowly getting replaced with more scientifically designed elements.

Summary

Co-rotating twin-screw extruders are versatile mixing devices that can contribute to the development of new plastic materials. This paper attempts to provide the latest development in designing the heart of this equipment. Already, a number of fractional lobe geometry has been used to form various elements. These have resulted in improving the melting and mixing characteristics of the extruder. Concerted efforts are being made to carryout further developmental activity to enable the plastics industry to realize complete benefit from this concept. Ultimately the task of an extruder is to carryout the right amount of work of the right kind (shearing, stretching, folding or squeezing) at the right place for the right amount of time. Plastics processing has been a technology's domain however still an art form. With newer elements and more detailed understanding, it would soon enter into a realm of exact science.

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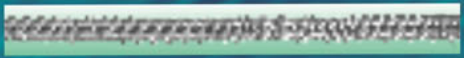

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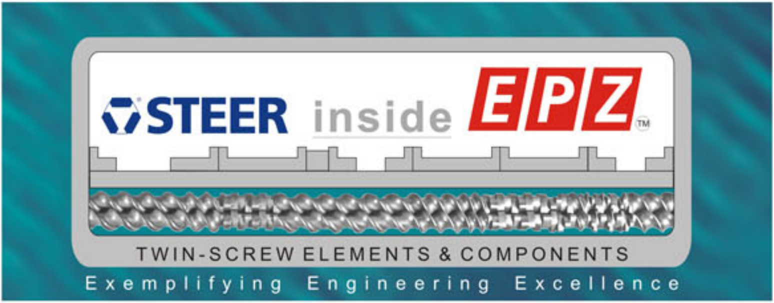
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