SHEAR UNIFORMITY IN CO-ROTATING TWIN SCREW EXTRUDER - A GEOMETRICAL STUDY OF SHEAR RATES IN A FULLY FILLED ZONE

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Abstract
Increase in screw speed results in increased localized shear rates in co-rotating twin-screw extruders due to higher radial and meta-radial shear. This results in shear non-uniformity which in-turn results in degradation of shear sensitive material. Shear rates induced by kneading elements with different geometries are studied in the axial
(longitudinal), radial and meta-radial shear planes. Elements with fractional lobed geometry having unequal tip angles show greater shear uniformity minimizing excessive shear in small regions. A careful study of the geometries of kneading elements and their shear distribution is provided for practical use in compounding application.

Introduction

Co-rotating Twin-screw extruders have the ability to work efficiently on plastic material by transferring mechanical energy to promote material fusion and physical interaction. This results in an increase in the uniformity of the composition and a reduction in the size of particles in the mixture. Work done on the material arises out of shear forces, extensional forces that cause elongation or stretching of material, compressive forces that result in pressure build-up and squeezing of the material and bending forces that cause fibers and layers to fold and interact. These forces occur in all three dimensions inside the extruder as defined by the axial plane and radial planes. In the case of kneading blocks, flow of material between elements in different radial planes creates metaradial shear in the material. In general, radial and metaradial shear rates are 10 to a 100 times greater in magnitude as compared to axial or longitudinal shear. Radial and meta-radial shear are not experienced uniformly by every macro-molecule or particle in the mix leading to the common difficulties of black specks and molecular weight loss in plastics processing. Improvements in the working of the extruder invariably lead to creating circumstances for uniformity in the radial and meta-radial shear rates, extensional flow patterns and frequent re-orientation.

Any effort to fully understand the working of a twinscrew extruder has to begin with a study of the geometry of twin-screw equipment. In 1978, Booy [1] conducted such a study based on about twenty years of work carried out in the field. Erdmenger [2] and Sakagami [3] are responsible for the collection of available geometry to design co rotating twin-screw extruder elements that have fully wiping twin-screw geometry. Since then, important innovations such as Eccentric Elements of Häring [5] and Fractional Lobed Elements of Padmanabhan [4] have revolutionized the effectiveness of the equipment. Padmanabhan [5] has provided an overview of the methods to construct the cross-section profile and subsequent transformation to Conveying Screw Elements, Kneading Blocks or Mixing Elements. With the application of Fractional Lobed geometry a larger choice of elements have now become available.

Directly employing kinematic methods akin to Booy, this paper attempts to provide recent information on the geometries of the elements and the accompanying shear rates, crucial to the application of a co-rotating twinscrew extruder for processing shear and temperature sensitive materials.

Shear Planes

Analysis of the working of a co-rotating twin-screw has been considered too complex for a “closed-form” or “direct” approach. Therefore, solutions using computational fluid dynamics (CFD) methods using finite elements operating under known boundary conditions are the typical route for analysis. By defining the shear planes and treating shear as a vector that is the result of combining the effects in three mutually separate shear planes, it will be shown that the analysis can be greatly simplified.

As in the case of single-screw extruders, there is a possibility of defining an axial (or longitudinal) plane at different orientations that are similar to each other. However, the presence of two screws complicates this approach. To simplify this while still retaining the integrity of the model, the axial plane is considered with the screw moving axially at a screw conveyor velocity (vs). The Shear rate in the axial plane can be taken to be the resultant of melt velocity (vm) and the screw conveyor velocity (vs). The difference between these two velocities over the distance of separation of the layers of the melt will provide the axial shear rate. For reverse lead elements, the screw velocity will be negative resulting in addition of the two velocities in scalar terms. Another shear plane that is perpendicular to the axial plane is the radial plane. In this radial plane, the screw rotation is taken into account. The radial plane will be shown to include the lateral plane that exists between two screws. Since one screw behaves as a dynamic barrel for the other screw, accounting for different positions of the screw is sufficient to measure the total shear. Kneading blocks offer-further challenges to the conventional model. It is however easy to include the working of the kneading blocks with a third plane that is perpendicular to both axial and radial plane. Since this plane is between two radial planes, it is termed the meta- radial plane.

Melt Velocity in a fully filled Zone
By requiring the continuity and conservation of mass flowing through the extruder, it is easy to establish that the average velocity of Melt in a fully filled zone is

vm = V / A (1)

where

vm – Average melt velocity
V – Volumetric Output in cc / s
A – Free Cross-sectional Area in cm2

The average velocity is the same regardless of forward, reverse or neutral kneading elements or reverse conveying elements. However, the velocity distribution is expected to vary with the variation being the highest in the reverse kneading and conveying elements.

Estimating mean axial shear rate
Starting with an assumption for convenience that the lead of elements used in a reverse element is equal to the center
distance ‘a’, the screw conveyor velocity is

vs= a * n (2)
where

n – Screw Speed in revolutions per second Mean axial shear rate _ [vs – vm] / (h/2) (3)

Where

h – Flight depth in cm

The Power requirement can be written with respect to the Torque requirement in the following manner:-

P = 2 _ n * 2T2 / 1,000 (4)

where P = Required Power in kW

T2 = Required Torque / shaft in Nm

Introducing the term, specific torque (Ts) as T2/a3 in the units “Nm/cm3” and considering a specific energy (Es) in the units “kWh / kg” and Bulk density (_) in the units “gm/cc” the equation for Volumetric Output can be written as

The Volumetric Output in cc/s

V = P / 3.6 _ Es (5)

V = 4 _ n Ts a3 / 3,600 _ Es (6)

For an extruder with a D/d = 1.71, where D is the Barrel Diameter, d is the Screw root diameter and a is the center
distance, it can be shown that the following approximations are valid :- A = a2 and h = a/4 .

Axial Shear Rate (1/s) _ 8 (1 + 4 _ Ts / 3,600 _ Es) n (7)

Since the second term is small, the mean axial shear rate can be approximated to 8n 1/s. It can be seen that the screw diameter does not influence the shear rate. In the case of high speed extruders with screw speeds of 1200 RPM, the mean axial shear rates will be about 200 1/s. At more conventional speeds, the axial shear rate will not exceed 100 1/s.

Estimating radial shear rate

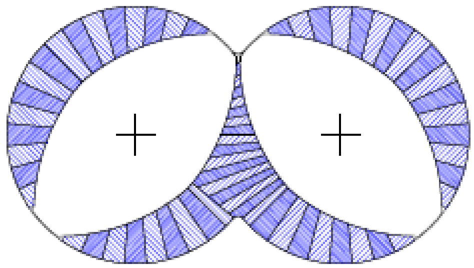
The schematic for calculating radial shear is shown in figure 1. The entire profile is divided into various regions with a thickness of 1mm. By using the average radial clearance in that region, the radial shear experienced by that fractional volume is calculated as

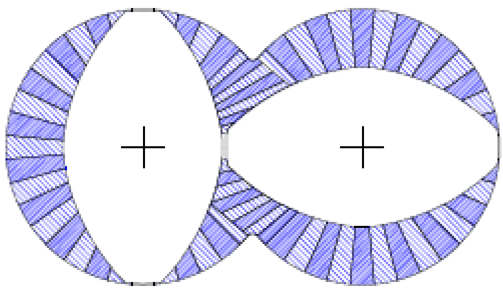
Radial shear rate = _ D n / c

where

D is the Barrel Diameter
Cn is the average radial clearance for that fractional volume

Radial shear rate in bi-lobed profile





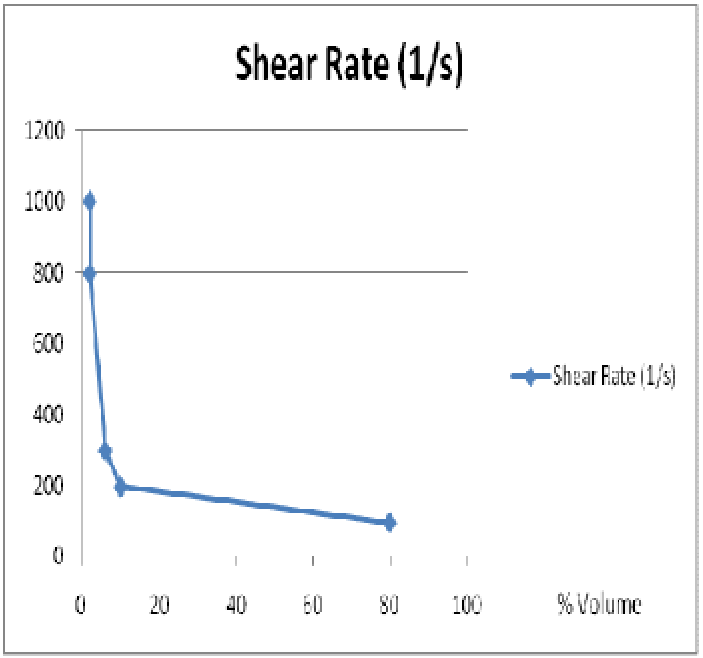
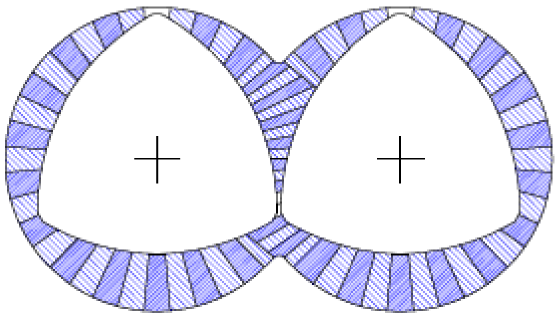


Figure 1. Radial shear rate for bi-lobed profile at 400 RPM

Figure 1 shows the shear rate distribution experienced by the melt surrounding a bi-lobed profile at 0 and 45 degree orientation. A very small portion of the melt experiences high shear intensity during the rotation. It is found that the shear rate curve is the same for both orientations. A very small volume of 1% is subjected to intense shear rate of over 800 1/s even at 400 RPM.

Radial shear rate in eccentric tri-lobed profile



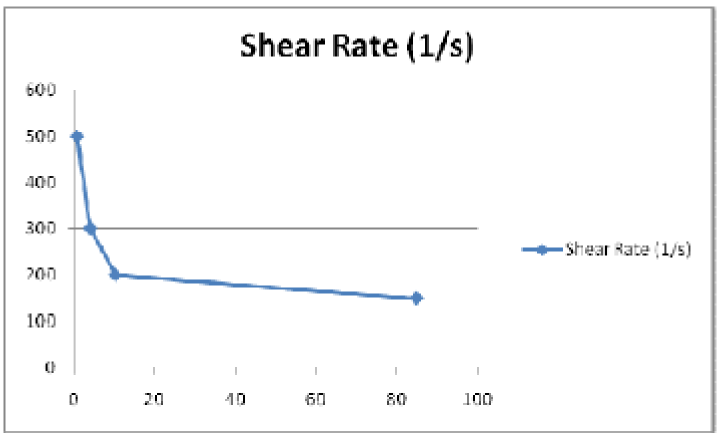


Figure 2. Radial shear rate for eccentric tri-lobed profile

Figure 2 shows that the eccentric tri-lobed profile is gentlest of the three profiles being studied. At 400 RPM, about 10% of the volume is subjected to shear rates that exceed 2001/s. A smaller volume of about 5% is subject to shear rates that exceed 300 1/s

Effect of Wear on radial shear
Depending on the melt viscosity, a moving tip will wipe rather than shear the melt. However, as the tip wears shear can develop at the tip as the material starts flowing across the tip. When the wear reaches about 1mm, a shear rate of _ D n will be reached. This diameter dependent shear rate is nearly 850 1/s for a 40mm extruder running at 400 RPM. In this condition 1% of the melt will experience this shear rate.

Estimating meta-radial shear rate for kneading blocks

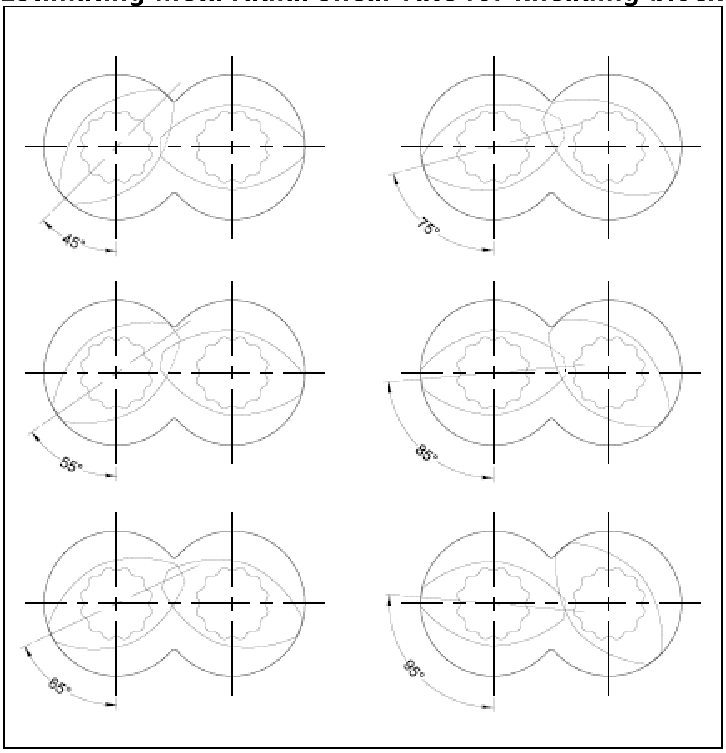


Figure 4. Development of Meta-radial shear in Bi-lobed Kneading blocks

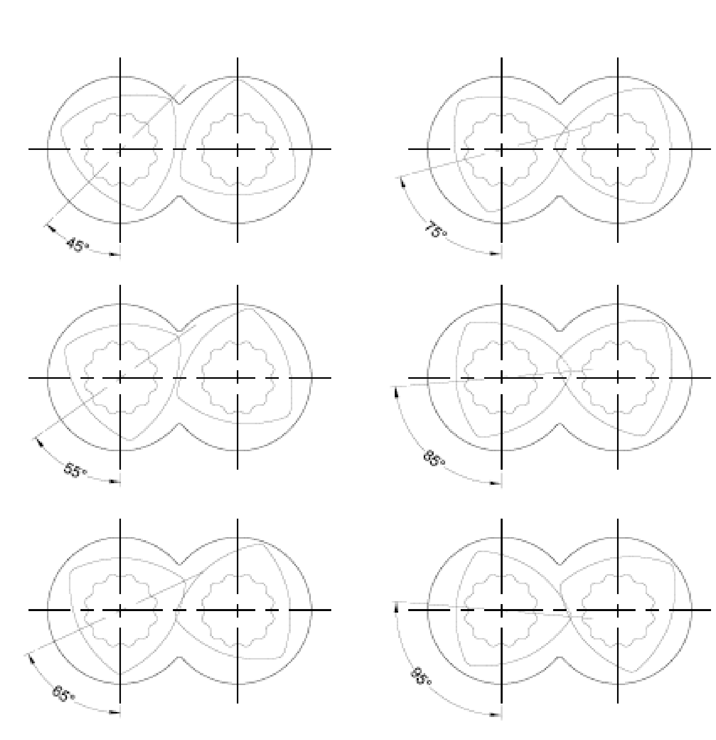


Figure 5. Development of Meta-radial shear in Eccentric tri-lobed Kneading blocks

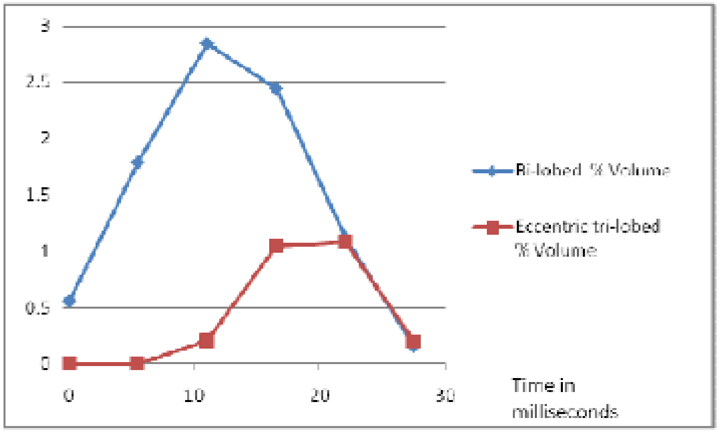


Figure 6. Volume Fraction subjected to intense shear rate of 1400 1/s @ 400 RPM

During rotation of the two screw shafts, the kneading blocks that are separated by a small axial clearance (typically c2 = .1 ~ .15 cm) cross over each other with a shear rate of 2 _ a n / c2. These high shear rates can reach nearly 10,000 1/s in large extruders (since this shear rate is dependent on the diameter). Acting over a small volume for milliseconds, the shear peaks can cause major processing problems with temperature and shear sensitive material.

Fractional Lobed Mixing Element

It is clear that radial shear is the major contributing factor in a co-rotating twin-screw extruder. Shear uniformity is as important as the need for higher shear intensity. Fractional Lobed based Mixing Elements that have the ability to produce this desired result is shown in Figure 7. Meta-radial shear is completely eliminated in these blocks while achieving higher shear intensity that is experienced by the largest possible volume.

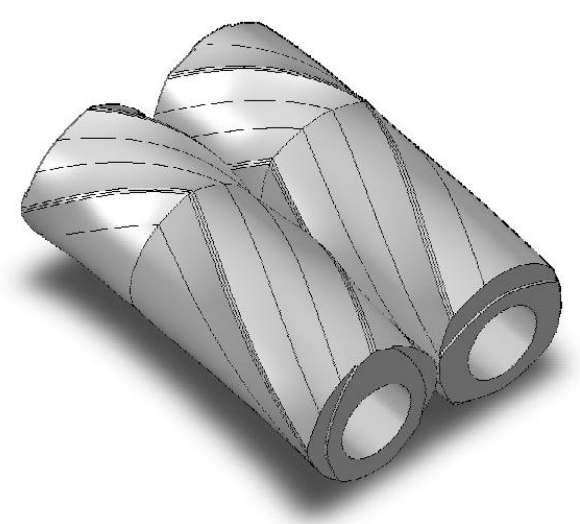
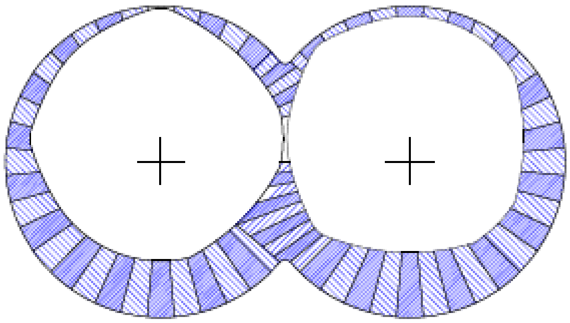


Figure 7. Mixing Elements using Fractional Lobed profile offered highest level of Shear uniformity and Intensity



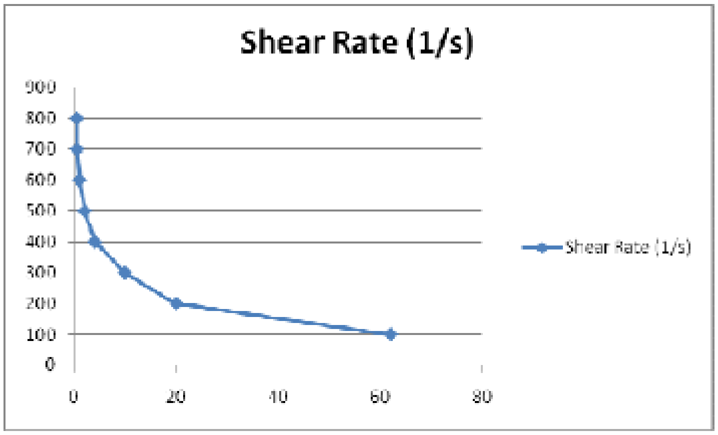


Figure 3. Radial shear rate for Fractional Four lobe profile

At a screw speed of 400 RPM, iIn the case of the Fractional Four lobed profile, the highest fractional volume (5%) will experience shear rate exceeding 400 1/s. Since this shear rate is directly proportional to screw RPM and since D/c is a constant, shear rates of 600 1/s, 800 1/s and 1200 1/s can be achieved at corresponding screw speeds of 600, 800 and 1200 RPM.

The Diameter ratio selected for this study is 1.71. For extruders that have a ratio of 1.55 and 1.49, the increase in shear rate is 15% and 25% respectively.

Conclusions

The fractional lobed mixing elements offer the ability to avoid effects of meta radial shear stresses that can contribute to material degradation. Methods have been presented to improve the understanding of corotating twin-screw extruders in terms of shear intensity and shear uniformity.

References

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