EFFECT OF ELEMENT GEOMETRY IN THE PROCESSING OF HIGHLY FILLED MATERIALS IN HIGH-SPEED DEEP-FLIGHTED TWIN-SCREW EXTRUDERS

Babu Padmanabhan, Steer Engineering Private Limited
Narayan Nanda Kumar, Sankhla Industries
Pradeep Bakshi, Steer Engineering Private Limited

Abstract
It is well known that deeper flights lead to improved efficiencies in a twin-screw extruder. The deeper flights result in the reduction of shear rates. This is taken advantage to increase the screw speed thereby maintaining the mixing rates and increasing the volumetric capacity of the machine. An improvement in process efficiency is realized due to the reduction in viscous dissipation per unit mass of material.

The localized increase in melt temperature due to the working of the kneading elements at high speeds is still a problem. Fractional lobed element geometry with unequal tip angles can be used to solve these problems. These new geometry can easily replace standard kneading elements. These fractional three and four lobed geometry are used in the processing of highly filled LLDPE with TiO2. Melt Temperatures and Dispersive Mixing effectiveness by in-line melt filtration data are discussed while processing with the known "Erdmenger" geometry

Introduction
The co-rotating twin-screw extruders have seen rapid evolution over the last 50 years. The major areas of its evolution that affects processing greatly are in the following.
- Geometry of the processing section
- Torque carrying capacity
- Length of the extruder
- Type and kind of feeding and venting systems
- Metallurgy of the processing section

The various generations have been clearly marked by the improvements in the first two areas, characterized by the Diameter Ratio and Specific Torque. Although the ability to process material has benefited from improvements in other areas, the increase in flight depth and the ability (power) to process the resulting higher capacity have been the important milestones. It is increasingly evident, from the paper by Kapfer and Häring (1) that extruders with deeper screw flights offer several advantages in processing viz. Higher intake capacity in starve feed, Lower melt temperature due to decreased shear stresses, Greater Devolatisation capacity, Better residence time distribution due to improved conveying efficiency. Further, the ability to process certain shear and temperature sensitive materials is greatly enhanced in an extruder with deeper flights.

Dispersion of pigments and fillers have been studied earlier. The mechanisms involved in dispersion of CaCO3 in Polypropylene has been studied by Gendron and Binet (2) and correlated to the residence time and shearing conditions. A theoretical approach to solid filler dispersion in a Twin-screw extruder using a general kinetic model for agglomeration/break-up based on chemical like equation has been correlated to actual results from the extruder by Berzin et. Al (3). A study by Flecke et. al (4) of the dispersion process in a co-rotating intermeshing twin-screw extruder results in a physical and mathematical model that can be used for simulation. It is evident from the work that the mechanism for dispersion is a combination of rupture and

erosion of the agglomerated particles. The re-agglomeration process is due to clustering and bonding of particles due to the presence of compressive forces.

While adding fine particles of Ti02 (8-10 microns in size) to a polymer, the particles are required to be wetted and distributed in the polymer in the extruder. However, even if the input material is free of agglomerated particles, the compressive forces generally present at the time of processing, especially melting can re-agglomerate (by clustering) the particle, resulting in the problem of dispersion in the later stages of the extrusion. In the absence of a special treatment or coating, this problem is accentuated in Ti02 and other pigments.

The mixing zone of a co-rotating twin-screw extruder is packed with a series of Kneading elements – a combination of Right, Neutral and Left handed elements to get adequate dispersion levels. The material may be processed only once or several times through the extruder to achieve the required level of dispersion. Further, the material may be screened while it exits the twin-screw extruder or in a separate extruder. The degradation of the material during several stages of processing is an important issue. A primary reason for the increase in temperature is due to the shearing forces that are used to break up the agglomerate by rupturing. The possibility of using erosion has a significant mechanism exists and is explored using the Fractional Lobed Geometry.

Fractional Lobed Geometry
The tip-angle is a critical component in the design of twin-screw extruders. The tip-angle for the known fully wiping co-rotating elements is given by the following equation 1.

$$t = \pi/n - (2 \cos^{-1} r) \quad (1)$$

where

't' - Tip angle
'n' - Number of lobes (or) flights (or) starts
'r' - Adjusted Center distance to Barrel-Diameter ratio

And

$$r = (c - \delta c)/(b - \delta b)$$

where
'c' - Distance between the center of the two bores (Center Distance)
'b' - Diameter of the bores (Barrel Diameter)
'δc' - Planned clearance (or) gap between the

elements

'δb' - Planned clearance (or) gap between the barrel and the element Note δc and δb are typically small values. It is evident that if the following condition 3 is satisfied, a lobe with a tip angle greater than zero can be formed.

$$\cos(\pi/2n) < r < 1 \quad (3)$$

The ratio of the center distance to the barrel diameter therefore controls the maximum number of lobes that are possible in the extruder with acceptable tip angle. An extruder constructed with a ratio closer to 1 can have many lobes with non-zero tip angle. Typical extruders have only two lobes ('r' = ~0.8) or three lobes ('r' =~0.9).

The end geometry has rotational symmetry with respect to the number of lobes. Higher number of lobes results in a smaller tip angle in the element. The surface of the various elements is obtained by helical or cylindrical and rotary transformations of the end geometry either in a continuous or intermittent manner.

Using the known geometry of twin-screw elements, more number of lobes can be designed for an extruder that has a smaller 'r'. This is achieved by using in the design a barrel diameter that is smaller than the actual barrel diameter until an acceptable 'r' (greater that 0.866 for three lobes) is achieved. The element so designed with more lobes is then mounted in an eccentric manner with respect to the center of the shaft. A group of such disks one after the other at a specific angle to one another forms a kneading element. These elements continue to be conjugate and are fully-wiping in nature.

The twin-screw elements have equal tip angles for all lobes. These limit the flexibility in designing the different type of elements that work in a twin-screw extruder has mentioned by Erdmenger (5). For example, the small tip angle in the eccentric tri-lobed kneading element leads to higher wear rate as only one of the tips operates closer to the barrel wall. Increasing the tip-angle would reduce the free volume available in the extruder. Further more, increasing tip-angle also makes the element become close to a circular shape.

Elements that can have differing tip-angles has been invented by Padmanabhan (6). These elements continue to work as conjugate pairs while satisfying the needs of twin-screw extrusion. The new element geometry provides greater flexibility in design of individual elements. The end geometry with unequal tip angle 't2' and 't3' shown in Figure 1 is that of one of the fractional elements. The fractional element classified as 1.3.80 means that it is formed as a transition of a single lobed and a tri-lobed geometry and the new geometry is one closer to the tri-lobed. Figure 2 shows a rotated position.

Figure 3 is the end geometry of another fractional element. The geometry is classified as 2.4.50. It is formed by a transition of a two-lobed and four-lobed element. The geometry is at a section that is half way through the transition.

Figure 4 is the end geometry classified as 1.2.50. This is half way between a uni-lobed and a bi-lobed element.

Figure 5 shows clearly the basis for the classification. The last fraction provides the location of the transition between the uni-lobed and bi-lobed element. The figure shows clearly the types of transition namely, the M type, T type and F type transition. These three types of transitions covers all possibilities of transitions. It may be noted that all three types of transitions are not necessary to generate fractional geometry.

If 'n' is the number of lobes on one end with less lobes and 'N' is the number of lobes on the other end with more lobes, then the condition for a perfect transition is that 'N/n' should be a whole number. In such an event, every intermediate section can give rise to a new element with unequal tip angle, a fractional element. Therefore, there exists an infinite set of these elements that can now be employed. The experiments will be conducted which just one of this very large collection of element geometry.

Experiment

Material

The experiments were carried out with the formulations shown in the Table 1. A pigment loading of 40% was chosen to investigate results arising primarily from the main feeder. Material was prepared in a High Speed Mixer. The LLDPE was used in the pellet form. 600 Kg of pre-mixed material was available for trials. The trials were conducted using a volumetric feeder calibrated for a flow rate of 100 Kg/hr.

S.No.	Ingredient	%w/w
1	LLDPE 50 MFI	58.1
2	R-104 TiO2	40.0
3	Plastaid – T	1.0
4	Antioxidant A1010	0.5
5	Calcium Stearate	0.4

Table 1 - Formulation Details

Equipment

The experiments were carried out in a Steer OMega® 40 extruder with the following features. Do/Di = 1.71 (r =0.792)1, L/D = 42, Specific Torque = 18.2 Nm/cm3 (75 kW @ 600 RPM) and capable of running to 1500 RPM. A screen 40/80/300/80/40 was used.

Processing Variables

The screw speed and configuration were the two key variables. Figure 6 shows the configuration of the extruder screw where the regular kneading blocks are formed with "Erdmenger" geometry. These are used for the Trials 1 and 2. Figure 7 shows the configuration with Fractional Four Lobed (1.4.50) kneading blocks used for the Trials 3 and 4. The kneading blocks have disks that have a relative twist angle of 60 degrees in a left-handed manner. These two configurations were run at 600rpm and 1200 rpm2. The zone temperatures are shown on the barrel segments in the Figures 6 and 7. The Kneading length in the mixing zone of both configuration are maintained to be 180mm.

	Trial1	Trial2	Trial3	Trial4
Configuration	Regular KB as in Figure 6	Regular KB as in Figure 6	Fractional KB as in Figure 7	Fractional KB as in Figure 7
Speed	600	1200	600	1200

Table 2 – List of Trials

1 Do/Di = 1 / (2r –1)
2 At a speed of 1500 RPM the melt temperature reached 300 deg C and yellowing of the melt was visible.

Procedure

A 100% pre-mix of all the ingredients was prepared in a high-speed mixer. The material was fed into the extruder using a volumetric feeder in a starve feeding mode into the intake barrel. Melt Pressure was sensed at two places before and after the screen. Melt Temperature were taken using a Non-contact Laser thermometer at the vents and at the Die at three time intervals during the experiment. Fresh Screens were placed before the breaker plate just before starting the trials each time.

The Process Details are as follows: Soon after the extruder was started at set extruder speed and input federate of 100Kg/hr, the Melt Pressure transducers indicated 3.0-3.6 MPa pressure

before the screen and 1.0 MPa pressure at the die. Within 30 seconds, the pressure stabilized to a lower value and the pressure fluctuations were within 0.2 MPa. The lower value of the fluctuation was always recorded at 30 seconds interval. Using the Non-contact Laser, 3 measurements were taken at each port and average value recorded at approx 5 minute intervals. The trial came to an end when the vent overflowed with the material.

Results and Discussions
Characterisation
Figure 8 shows the variation of melt pressure at the screen. Figure 9 shows the variation of melt temperature during the four trials3. There is roughly 40% improvement in time for clogging between 600 and 1200 RPM trials with both configurations. Initially, the configuration with the fractional element results in lower pressure buildup. However, the increase in pressure matches for both configuration as the trial progresses.

The melt temperature results are tabulated in Table 3.

	Trial1	Trial2	Trial3	Trial4
Die	200	231	192	215
Vent 2	220	275	212	245
Vent 1	182	212	180	212

Table 3 – Melt Temperature Results

3 The pressure variation recorded could have been slightly inaccurate due to the lack of homogeneous mixture of
powder-granule in the pre-mix. A powder-powder premix experiment will be carried out. Melt temperature probes will be used during the next set of trials to achieve better repeatability of temperature measurements.

The temperature at Vent 1 forms the base-line since this is just after melting. With respect to this temperature, there is about 25% increase in the melt temperature just after mixing with regular kneading blocks. There is only about 15% increase in melt temperature just after mixing in the case of Fractional lobed elements. Significantly, there is a 5% drop in melt temperature at 600 RPM and 10% drop in temperature at 1200 RPM with fractional lobed kneading blocks.

The Specific Energy values for the Trials are shown in Table 4.

	Trial1	Trial2	Trial3	Trial4
Specific Energy (kwhr/Kg)	0.202	0.298	0.225	0.338

Table 4 – Specific Energy Values

It is important to note that despite decrease in melt temperature, more energy is utilized. The configuration with fractional lobed is utilizing 10% more energy compared to the other. Since melt temperature is lower by a significant moment, it is estimated that 12- 15% higher effort is being directed toward mixing. Since dispersive mixing by rupture would involve shear and increase in melt temperature, it is gathered that this work is directed towards erosion of the particles. Further work in carefully separating the effects of the two mechanisms needs to be conducted.

Rheology
Melt Indexer results4
Table 5 provides the result of Melt Index values measured using a standard apparatus. These values are for samples collected at a time approximately at the middle of the trial.

	Trial1	Trial2	Trial3	Trial4
MI Val	51.5	50.65	52.35	51.65

Table 5 – Melt Index Values

Conclusions
Firstly, it is noted that with fractional elements, it is possible to run highly filled material (40% TiO2 in LLDPE) at high speeds of 1200 RPM. Additionally, it is demonstrated that with a good selection of geometry it is possible to finely control the process further than hitherto considered possible with standard elements. The fractional lobed geometry used in this experiment was selected based on certain observations on the changes in cross-section during rotation of the corresponding geometry. The motivation was to avoid

4 OIT and YI results are awaited at this time. high pressure points during the full 360 degree turn of the flights. The experiment reveals that assumed potential of the geometry appears to be justified. There are many other enhancements hidden within the vast collection of other geometry that are possible.

References
1. Klaus Kapfer, Erwin Häring; "Deeper Screw Flightsoffer new opportunities for Co-rotating twin screw extruders", ANTEC papers 2002.

2. Richard Gendron, Daniel Binet; "State of Dispersion :Polypropylene Filled with Calcium Carbonate". Journal of Vinyl & Additive Technology, March 1998, Vol. 4, No. 1

3. F. Berzin and B. Vergnes; P. G. Lafleur and M. Gremla; "A theoretical approach to solid filler dispersion in a Twin-screw extruder". Polymer Engineering and Science, March 2002, Vol. 42, No.3.

4. J. Flecke, H. Potente, K. Kretschmer; "A physicomathematical model for the dispersion process in a co-rotating intermeshing twin-screw extruder". ANTEC papers 2000.

5. US Patent 3,254,367 Screw Apparatus, Rudolf Erdmenger, July 1966

6. US Patent 6,783,270B1 Fractional Elements, Babu Padmanabhan, Aug 2004
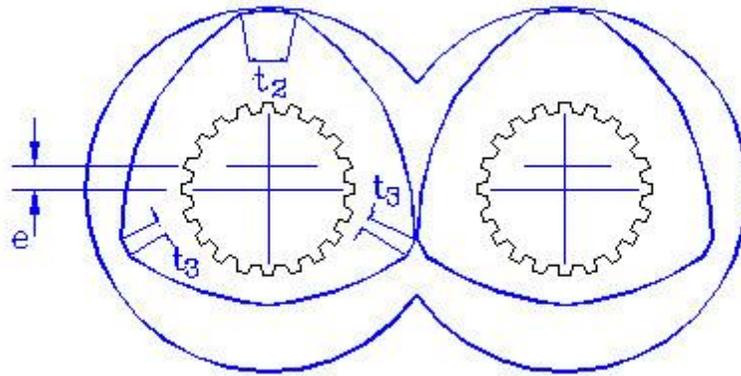
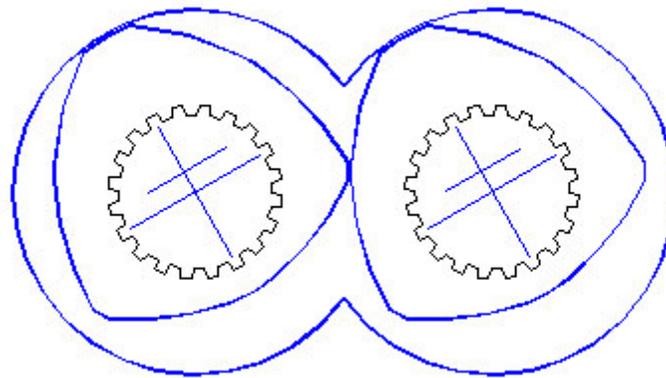Figure 1 - Fractional Tri-lobed Element Geometry 1.3.80

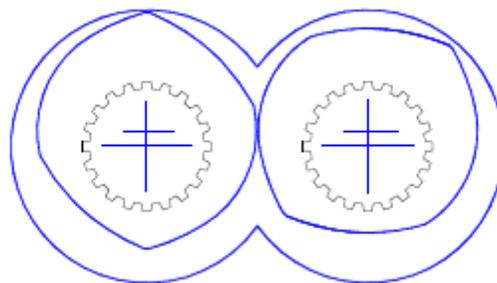Figure 2 - Rotated Position of Fractional Geometry 1.3.80

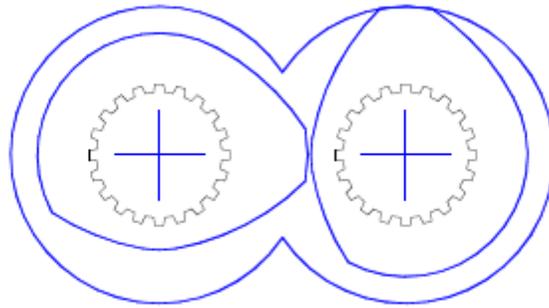Figure 3 - Fractional Four-lobed Element Geometry 1.4.50

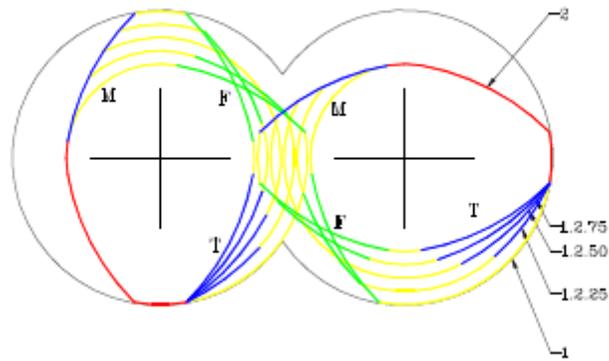Figure 4 - Fractional Two-lobed Element Geometry 1.2.50
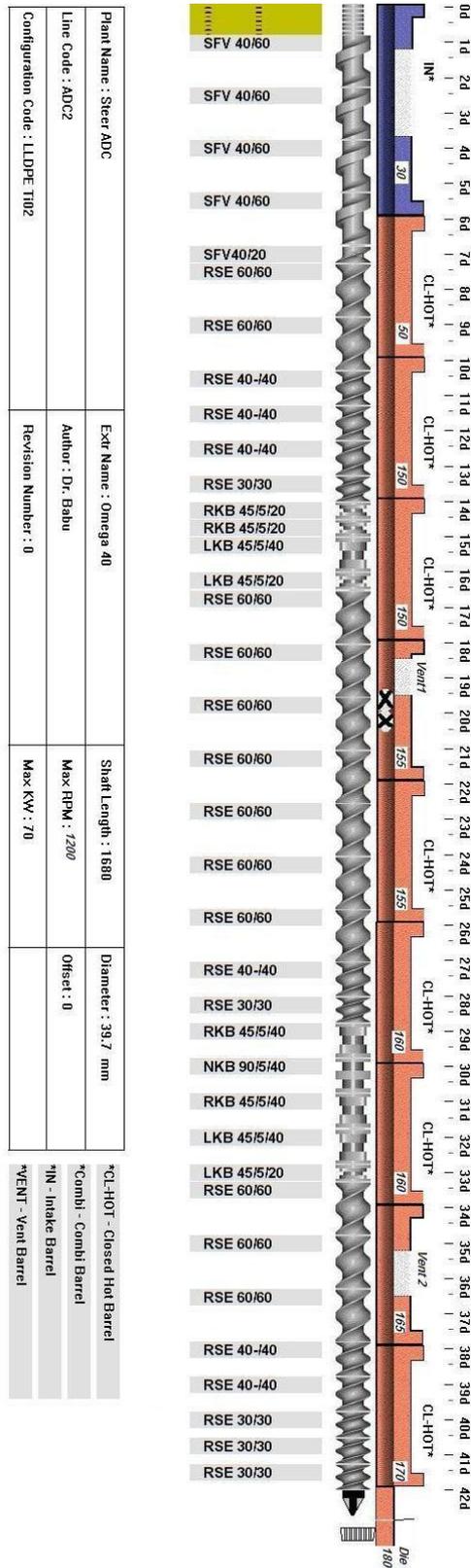

Figure 5 - Generation of Fractional Geometry

Figure 6 - Configuration with Regular Kneading Blocks used for Trial 1 and 2

Plant Name : Steer ADC
Line Code : ADC2
Configuration Code : LLDPE Tio2 Fractional

Extr Name : Omega 40	Author : Dr. Babu	Revision Number : 0
Shaft Length : 1680	Max RPM : 1200	Max KW : 70
Diameter : 39.7 mm	Offset : 0	
*CL-HOT - Closed Hot Barrel	*Combi - Combi Barrel	*IN - Intake Barrel
		*VENT - Vent Barrel

Element list:
SFV 40/60
SFV 40/60
SFV 40/60
SFV 40/60
SFV40/20
RSE 60/60
RSE 60/60
RSE 40-/40
RSE 40-/40
RSE 40-/40
RSE 30/30
RKB 45/5/20
RKB 45/5/20
LKB 45/5/40
LKB 45/5/20
RSE 60/60
RSE 60/60
RSE 60/60
RSE 60/60
RSE 60/60
RSE 60/60
RSE 60/60
RSE 40-/40
RSE 30/30
FUKB 60/7/60A
FXKB 60/7/60
FUKB 60/7/60B
RSE 60/60
RSE 60/60
RSE 60/60
RSE 40-/40
RSE 40-/40
RSE 30/30
RSE 30/30
RSE 30/30

Barrel section labels: IN* — 30 — CL-HOT* — 50 — CL-HOT* — 150 — CL-HOT* — 150 — Vent1 — 155 — CL-HOT* — 155 — CL-HOT* — 160 — CL-HOT* — 160 — Vent 2 — 165 — CL-HOT* — 170 — Die — 180
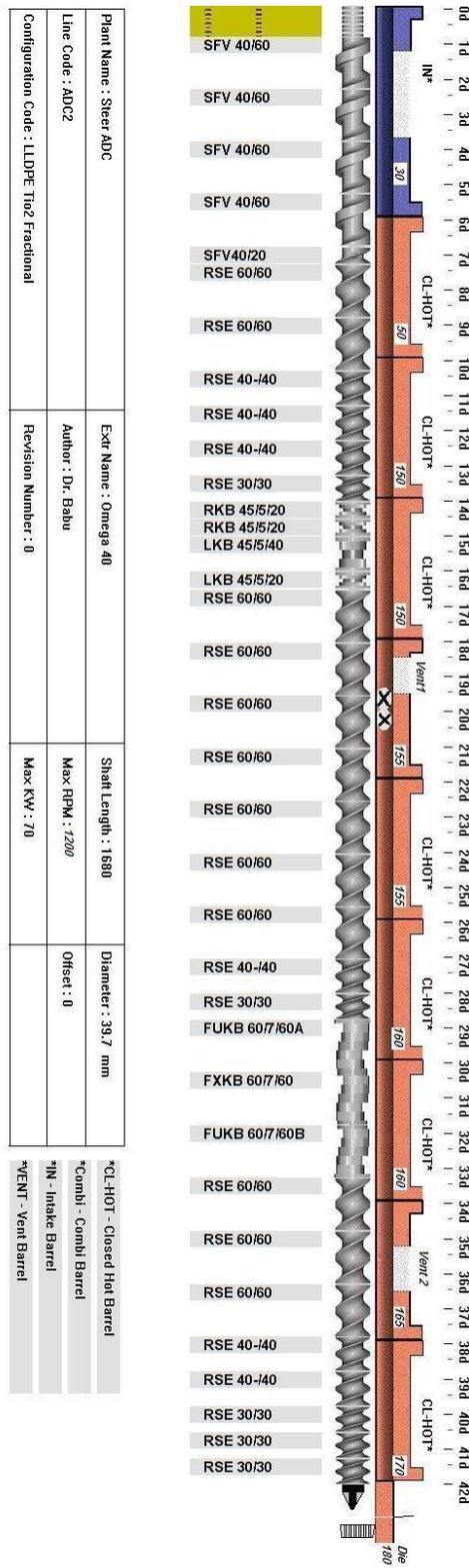
Scale: 0d – 42d

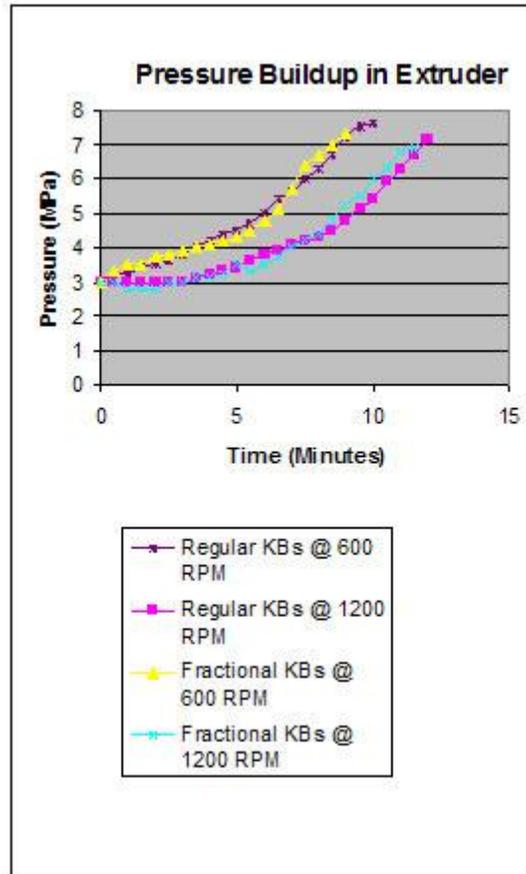Figure 7 - Configuration with Fractional Kneading Blocks used for Trial 3 and 4
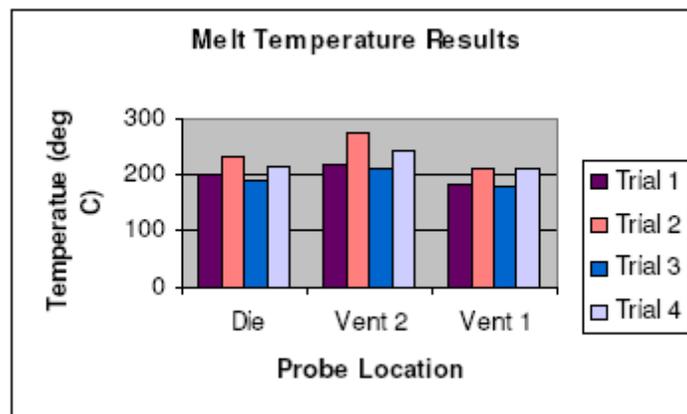
Figure 8 - Pressure at the Screen

Figure 9 - Melt Temperature results

Key Words : Twin screw extrusion, Dispersive mixing, Low melt temperature.