VALIDATION OF RESIDENCE STRESS DISTRIBUTION APPROACH USING 1-D COMPUTER SIMULATIONS

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Abstract

The compounding process in the twin-screw extruder (TSE) comprises the dispersive and distributive mixing. Dispersive mixing has been the primary agent that influences the mixing of polymer melt in the TSE. It has been difficult to predict the dispersive mixing in the TSE due to the complex flows that develop in the TSE. The Residence Stress Distribution (RSD) approach has been used to quantify the amount of polymer melt that experiences a particular amount of stress, when processed in a co-rotating twin screw extruder. In order to predict the stress history developed in the twin-screw extruder, the percent break up of CAMES (Calibrated Micro Encapsulated Sensor) beads have been used. Percent Break up (%BU) values obtained across an operating condition domain are used to generate a predictive equation using JMP statistical software, in order to express % BU as a function of screw speed (N) and specific throughput (Q/N). In order to provide an insight into the RSD results, a 1-Dimensional Twin Screw Extrusion software called Ludovic is used. Based on the screw geometry and operating conditions, Ludovic simulates a set of results such as the temperature, viscosity and shear rate experienced by the polymer melt in the extruder. These results have helped understand the percent break up results obtained from the RSD experiments. An independent validation of the Residence Revolution Distribution (RRD) and Residence Volume Distribution (RVD) has been performed using the computer simulations.

Introduction

Extrusion is a viable process that has been used to create a variety of products. The screw extruders are being used to manufacture metals, plastics, pharmaceuticals. Twin screw extruders are the most commonly used screw extruders to manufacture plastics with enhanced properties. Twin screw extruders compound additives (fillers) into the polymer melt, as it helps improve the properties of the polymer and helps enhance its usage. The amount of mixing that the polymer experiences in the extruder is an important factor in order to attain the desired characteristics. The two different types of mixing in the extruder are distributive and dispersive mixing. Distributive mixing is the reduction of scale of separation of two miscible materials. Dispersive mixing is the rupture of agglomerates into smaller particles, which are dispersed into the polymer melt. The nature of the stress that the polymer is subjected to i.e. distributive or dispersive mixing, is determined by the configuration of the screw elements used in the twin screw extruder.

Studies have been conducted in the past to record and analyze the stress history and residence time distributions in an extruder. Experiments have been conducted in order to correlate the Time Distribution and Stress history, through the use of Peclet numbers [1], which have been used to relate Residence Time Distribution (RTD) with the mixing intensity. However, the stress history could not be interpreted using typical residence distributions, as it only provides the history of the axial flow in the extruder. Experiments to quantify the stress experienced by the polymer melt in the extruder, have been conducted. Curry et al. [2] used the percent breakage of hollow glass spheres, to quantify the stress in the twin screw extruder. Despite being able to correlate the screw speed (N) with the stress history, the method was time intensive and error prone, as they had to manually count the number of broken glass spheres.

The Residence Stress Distribution (RSD) approach was developed by Bigio et al. [3], as a method to characterize dispersion, through stress quantification in the twin-screw extruder. Stress beads (polymeric beads) with a critical stress limit, were dropped into the polymer melt before the mixing section. The beads that experience stress greater than the critical stress limit rupture, releasing an encapsulated dye into the polymer melt. The number of beads that experience the stress greater than, or equal to the critical stress limit, are expressed as percent break-up (%BU). %BU can be used as a measure to determine the amount of material that undergoes a particular amount of stress in the twin screw extruder, and can be used to relate to the degree of dispersion.

The RSD approach has been used to measure the %BU, at different operating conditions, for different screw configurations on several extruder scales, using variable strength stress beads [3-5]. A robust design of experiment approach was formulated in order to perform a statistical analysis of the percent break-up results using the Central Composite Design (CCD) grid approach [6]. These experiments were performed to evaluate the effect of screw speed (N) and specific throughput (Q/N) on %BU. Each of these experiments have shown the effects of N and Q/N on %BU, to be significant [3-5]. The second order terms such...
as $N^2$, $(Q/N)^2$ and $Q$ (interaction of $N$ and $Q/N$) are found to be non-significant. Recent experiment conducted on using 3 parameter residence stress distribution, has demonstrated that dispersive mixing is a function of $N$, $Q/N$ and Barrel Temperature ($T_b$) [7].

As a continuation to the above mentioned experiments, this research focuses on using a twin screw extrusion simulation software called Ludovic, which is a 1-D simulation software that models the working of a TSE [8]. This software is capable of generating output such as the temperature of the polymer melt, viscosity, shear rate and degree of fill along the corresponding point on the TSE, based on the screw configuration and the operating conditions input by the user into the software. The aim of this paper is to focus on the results generated by Ludovic, in order to understand and explain the %BU results obtained from the RSD experiments conducted for several screw configurations on the TSE [3-7].

**Materials**

The base polymer used for this experiment was Low Density Polyethylene (LDPE), Petrothene NA 206, which was supplied in pellet form by Equistar Chemicals. The LDPE has a density of 0.918 g/cc and melt flow of 13.5 g/10 min.

CAMES (Calibrated Microencapsulated Sensor) beads are the stress beads used for the experiment. These are manufactured by Mach 1 Inc, King of Prussia, PA. The stress history in the twin screw extruders are measured with the help of the CAMES beads, which are designed to rupture, based on their wall thickness and diameter, upon encountering critical stress in the mixing section of the extruder. Upon rupture, CAMES beads release an encapsulated dye into the polymer melt. AUTOMATE Blue 8A, manufactured by Rohm & Haas Co., is the dye used in the CAMES beads. Reference shots, which comprise the same dye used in the CAMES beads, are used to provide RTD, as it represents all the path travelled, a situation similar to when every stress bead is broken (100% break up of CAMES beads). The reference dye shots are made by dissolving pellets of polystyrene in xylene and adding dye to it.

**Equipment**

Coperion ZSK 18mm fully intermeshing, co-rotating Twin Screw Extruder, with a L/D ratio of 41 was used for the experiment. The extruder comprised a total of 10 barrels. The barrels leading to the mixing section are set to a temperature of 150º C. The mixing section is set at a barrel temperature of 125º C. The barrel in between the mixing section and the die zone is set at 135º C. The die zone is set at a barrel temperature of 140º C. Wide Kneading Block and Narrow Kneading block geometry were considered for the experiment. The mixing sections had an axial length of 24mm.

![Image](Image 390x632 to 415x675)

**Figure 1: 24mm Narrow and Wide Mixing Section**

Figure 1 shows the mixing sections considered for the experiment. Both the mixing sections are followed by a half reverse turn of pumping element. The entire screw configuration can be found in Appendix A.

Ludovic Simulation Software has been used to analyze and interpret the results generated for the input screw geometry and operating conditions. Ludovic is a 1-Dimensional twin screw extrusion software that has been developed by Sciences Computer Consultants (SCC) and it helps model the working of a twin-screw extruder. The screw configuration that the individual wants to design, is input into the software along with specifications on the operating conditions i.e. Screw speed ($N$) and Feed Rate ($Q$). The polymer matrix that needs to be processed in the twin-screw extruder can be retrieved from the Ludovic library that has an entire database of the polymers that are used in the industry. The user can provide custom values for the polymer matrix (i.e. melt density, latent heat etc.) and the software uses Power Law Model, Carreau Yasuda Law to calculate the polymer viscosity based on the input values.

**Experiment**

This experiment consists of two phases. The first phase is to use the RSD approach to generate the percent break-up (%BU) results. The percent break up is obtained by comparing the RSD to RTD. RSD is obtained when the stress-sensitive CAMES beads are dropped into the polymer melt (LDPE), upstream of the mixing section in the TSE. RTD is obtained by injecting the same dye used in the CAMES beads, and this represents a situation similar to the one where there is 100 % bead break-up. The CAMES beads rupture and release the encapsulated dye into the polymer melt, when the stress applied on the CAMES beads in the mixing section, overcomes the critical stress limit. %BU is calculated as the ratio of the area under RSD to the area under the RTD curve.

The Design of experiment (DOE) approach was used to minimize the number of operating conditions, that would be required to run the experiment. The operating conditions for the experiment were considered for a set of $N$ and $Q/N$ values. This was used to analyze the effect of $N$ and $Q/N$ on %BU within the operating condition domain. A total of 9
operating conditions were chosen using the Central Composite Design (CCD) grid.

Figure 2: Operating Conditions comprising N and Q/N

Figure 2 shows the set of 9 operating conditions considered for the experiment, where the X axis comprises a range of screw speeds (in RPM), while the Y axis comprises a range of specific throughputs (ml/rev). $\bar{m}$ represents the feed rate (lb/hr).

The %BU values generated for each of the operating conditions were formulated into a predictive equation in terms of the significant operating conditions. This was accomplished using JMP 12.2, which is a statistical analysis software, used to analyze and interpret data visually and graphically. In order to consider only the significant terms, a significance level of 0.05 was chosen in order to determine the significance of the operating conditions (N, Q/N) and their second order terms (N², (Q/N)²) and their interaction (Q). The data on the %BU was input into JMP, which generates the predictive equations using the standard least squares fit-model methodology. The predictive equations modeled %BU as a function of N and Q/N along with an intercept value.

$$\%BU = I + A * N + B * \left( \frac{Q}{N} \right)$$  \hspace{1cm} (1)

From Equation 1, the predictive equations can be seen as a function of only N and Q/N. The intercept value is represented by I, A and B represent the coefficient values for N and Q/N. These values are obtained using the least square fit method. The effects of the second order terms on %BU are considered insignificant, based on the results generated using JMP.

The second phase of the experiment is to interpret the %BU results using the results provided by Ludovic simulations. The screw design for Ludovic simulations have been designed based on the actual 18mm Co-Rotating Twin Screw Extruder screw configurations.

Figure 3: Screw Configuration for Ludovic Simulations

Figure 3 represents the screw configuration that was used to perform the Ludovic simulations. The feeding section starts from the right and moves to the left, where the extruded polymer exits the extruder from the die. The blue screw elements represent the forward conveying elements, while the red screw elements represent the reverse conveying elements and the green elements represent the Kneading block elements. The mixing section comprises of the kneading blocks (24mm narrow and wide K.B are the screw geometries considered for this experiment) followed by the reverse conveying element. The simulations were performed for each of the operating conditions represented by Figure 2. LDPE was chosen as the base polymer for the experiment and the datasheet for the polymer can be retrieved from the Ludovic library, which comprises a database of a wide variety of polymers. Once all the conditions necessary to run the simulations, are input into Ludovic, the output is generated. The Ludovic output comprises Temperature, Pressure, Viscosity, Shear Rate etc. of the polymer melt, along each individual coordinate point on the screw. This gives the flexibility to understand the variations in each of the output values at different points along the screw length in the extruder model. The output values obtained for each of the parameters listed above have been statistically analyzed using JMP 12.2, in order to generate the predictive equations.

Result

The results presented below have been recorded for the screw configurations comprising a 24mm long mixing section. Narrow K.B and Wide K.B sections shown in Figure 1 have been used, in order to compare the results based on the differences in the screw geometry.

Experimental Results

Percent Break – Up

The percent break-up (%BU) values for the experiment conducted, for the 18mm (TSE) using LDPE for each of the operating conditions mentioned in Figure 2, are presented using the 2D- CCD grids. Each coordinate point will show the average %BU value at that point. The average was taken from 2 to 3 data points at each set of operating conditions.
Figure 4: %BU values for 24mm Narrow Mixing Section

Figure 5: %BU values for 24mm Wide Mixing Section

Figure 6: Temperature in the Mixing section of Narrow and Wide 24mm K.B

Table 1: Predictive equations for %BU as a function of N and Q/N

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Intercept</th>
<th>Coeff. N</th>
<th>Coeff. Q/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow</td>
<td>55.3</td>
<td>4.11</td>
<td>4.54</td>
</tr>
<tr>
<td>Wide</td>
<td>58.5</td>
<td>5.53</td>
<td>4.48</td>
</tr>
</tbody>
</table>

Table 1 represents the predictive equations for %BU as a function of N and Q/N. The trends observed in the CCD grid (Figure 4 and 5) have been quantified using the predictive equations from Table 1. The intercept values reflect on the average of the %BU values obtained across all the coordinate points on the CCD grid. The coefficient values for N and Q/N represent the changes in %BU as the N and Q/N variables change across the CCD grid. The data from Table 1 reveals that wider K.B have a higher %BU compared to narrow K.B. A higher coefficient of N for wider K.B reveals that change in %BU is higher for change in N across the CCD grid. The coefficient of Q/N is almost similar for the wide and narrow K.B which implies that the change in %BU is similar for both narrow and wide K.B as Q/N changes. For narrow K.B, Q/N has a more significant impact on %BU due to a higher coefficient of Q/N than N. For wider K.B, N has a more significant impact on %BU due to higher coefficient of N than Q/N. The wider K.B exhibit a higher %BU compared to narrow K.B due to the fact that wider kneading blocks wider paddles and act as better dispersive mixers compared to narrow kneading blocks which exhibit a lower level of stress and are better distributive mixers.

Ludovic Simulation Results

The experimental results revealed data which implies that wider kneading blocks exhibit higher stresses compared to narrow kneading blocks, leading to higher %BU values. These results could be explained better with the help of Ludovic simulations, which gives a better insight and understanding of the experimental results. The output provided by Ludovic focus on the temperature, pressure, viscosity, shear rate and shear stress in the mixing section of the extruder.

Temperature in the Mixing Section

Based on the screw model (Figure 3) and the operating conditions (Figure 2) input into the software, output obtained from performing the simulations provided the temperature of the polymer melt (°C) along the entire length of the extruder i.e. from the feed section to the die. The temperature of the melt in the mixing section was considered in order to focus on the %BU results obtained from the experiments.
From the Figure 6, it can be seen that at a constant (Q/N), the temperature increases with screw speed, which is due to the fact that higher screw rotations generate friction between the barrel walls and the polymer melt which leads to a spike in the temperature. At constant N, when the (Q/N) is increased, the temperature decreases. It is posited that the fill length upstream to the reverse elements is minimally increased; whereas the time in the mixing section is greatly decreased. The temperature data is input into JMP to get predictive equations for N and Q/N for the different screw geometries.

### Table 2: Predictive equations for Temperature as a function of N and Q/N

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Intercept</th>
<th>Coeff. N</th>
<th>Coeff. Q/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow</td>
<td>258.5</td>
<td>6.91</td>
<td>-12.41</td>
</tr>
<tr>
<td>Wide</td>
<td>263.1</td>
<td>5.83</td>
<td>-12.67</td>
</tr>
</tbody>
</table>

Table 2 reveals the predictive equations for temperature in the mixing section as a function of N and Q/N. The data from Table 2 reveals that the intercept value for temperature in the mixing section is higher for the wider K.B compared to narrow K.B, which implies that the average of T<sub>mix</sub> (temperature in the mixing section) across the CCD grid is higher for wider K.B compared to narrow K.B. Q/N has a more significant effect on T<sub>mix</sub> compared to N as the coefficient for Q/N is higher than the coefficient for N. For narrow K.B, change in T<sub>mix</sub> is higher, with change in N variable, compared to wider K.B. The change in T<sub>mix</sub> is almost similar for the wider and narrow K.B, for change in Q/N variable across the CCD grid.

### Maximum Pressure in the Mixing Section

The pressure generated in the mixing section is a key parameter to understand mixing in the twin-screw extruder. The results can be seen in Figure 7, which represents the maximum pressure (bars) attained in the mixing section for each corresponding point in the CCD grid for the different screw geometries.

At constant (Q/N), as screw speed (N) is increased, the pressure increases. Similarly, as specific throughput increases at constant N, the pressure increases. This is due to the fact that increase in specific throughput increases the degree of fill in the screw channel which implies a higher pressure in the conveying direction to overcome the back pressure. The data on maximum pressure is input into JMP in order to get the predictive equations for the corresponding screw geometries.

### Table 3: Predictive Equations for Max. Pressure in the Mixing section as a function of N and Q/N

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Intercept</th>
<th>Coeff. N</th>
<th>Coeff. Q/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow</td>
<td>22.84</td>
<td>0.725</td>
<td>3.29</td>
</tr>
<tr>
<td>Wide</td>
<td>21.81</td>
<td>1.03</td>
<td>3.27</td>
</tr>
</tbody>
</table>

Table 3 reveals the predictive equations for P<sub>max</sub> (Maximum Pressure) in the mixing section as a function of N and Q/N. The intercept value for P<sub>max</sub> is higher for narrow K.B compared to wider K.B, as the average of P<sub>max</sub> in the mixing section across the CCD grid is higher for narrow K.B compared to wider K.B. Q/N has a higher significance on P<sub>max</sub> compared to N as the coefficient for Q/N is higher than N. The coefficient for N is higher for wider K.B compared to narrow K.B, which implies that change in P<sub>max</sub> is higher for wider K.B when the N variable changes across the CCD grid. The coefficient for Q/N is almost similar for wider K.B compared to narrow K.B.

### Viscosity

Results for the viscosity of the polymer melt (Pa-s) along the screw profile of the extruder can be seen in the Figure 8 below. The viscosity values have been recorded at the highest temperature zone in the mixing section of the twin-screw extruder.

Figure 8: Viscosity at T<sub>max</sub> for narrow and wide 24 mm mixing section

When N is increased at a constant (Q/N), the viscosity decreases which can be understood from the fact that as the screw speed increases the temperature increases in the screw profile which results to the decrease in viscosity. When (Q/N) is increased at a constant N, the viscosity is found to
increase which can be related to the fact that a higher specific throughput leads to the reduction in temperature in the screw channel, and a drop in the temperature values tend to increase the viscosity. The data on viscosity is input into JMP in order to get the predictive equations for the corresponding screw geometries.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Intercept</th>
<th>Coeff. N</th>
<th>Coeff. Q/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow</td>
<td>316</td>
<td>-64.75</td>
<td>44.91</td>
</tr>
<tr>
<td>Wide</td>
<td>301</td>
<td>-50.41</td>
<td>44.93</td>
</tr>
</tbody>
</table>

Table 4 reveals the predictive equations for Viscosity at Maximum Temperature (µ) in the mixing section as a function of N and Q/N. The intercept value for µ is higher for narrow K.B compared to wider K.B, as the average of µ in the mixing section is higher for narrow K.B compared to wider K.B. N has a higher significance on µ compared to Q/N as the coefficient of N is higher than Q/N.

**Shear Rate**

The shear rate (s⁻¹) values for the polymer melt have been calculated at the highest temperature region in the mixing section.

\[
\dot{\gamma} = \frac{(\pi D N)}{h}
\]

Figure 9: Shear Rate in the 24mm Narrow and Wide Mixing section

The results calculated from Ludovic implies that shear rate is only a function of screw speed. At a constant Q/N, when the screw speed is increased the shear rate increases. At a constant N, when the specific throughput is increased, the shear rate remains constant. Change of screw geometry from narrow to wide kneading block does not have an impact on the shear rate values.

Shear rate is defined by the relation

\[
\dot{\gamma} = \frac{(\pi D N)}{h}
\]

Which implies that shear rate varies with the screw speed and the base diameter of the screw.

The data on shear rate is input into JMP in order to get the predictive equations for the corresponding screw geometries.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Intercept</th>
<th>Coeff. N</th>
<th>Coeff. Q/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow</td>
<td>104.92</td>
<td>21.7</td>
<td>21.7</td>
</tr>
<tr>
<td>Wide</td>
<td>104.92</td>
<td>21.7</td>
<td>21.7</td>
</tr>
</tbody>
</table>

Table 5 reveals the data for shear rate in the mixing section as a function of N only. Constant Intercept value implies that the changes in screw geometry (i.e. Narrow and Wide K.B in Mixing Section) does not have an impact on the shear rate experienced by the polymer melt.

**Shear Stress**

Shear stress (kPa) is calculated from the shear rate and viscosity (η) values obtained using the Ludovic Simulations. For the purpose of simplifying the calculations, the following equation was used to calculate the shear stress values.

\[
\tau = \dot{\gamma} \times \eta
\]

From Eq.2, the shear stress values were calculated for each of the operating conditions. The results can be seen in Fig 10.

Figure 10: Shear Stress in the 24mm Narrow and Wide Mixing Section

Figure 10 reveals the data on shear stress (kPa). At a constant (Q/N), the shear stress increases with the increase in N (screw speed), which is due to the fact that the shear rate increases with N at a higher rate compared to the viscosity, which results in an increase in the shear stress value. At a constant N, when the Q/N is increased, the shear stress increases which can be attributed to the fact that viscosity increases with increase in specific throughput and shear rate remains a constant at constant N. The data on shear stress is input into JMP in order to get the predictive equations for the corresponding screw geometries.
Table 6: Predictive equations for shear stress as a function of N and Q/N

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Intercept</th>
<th>Coeff. N</th>
<th>Coeff. Q/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Narrow</td>
<td>33.49</td>
<td>1.26</td>
<td>4.63</td>
</tr>
<tr>
<td>Wide</td>
<td>31.7</td>
<td>1.84</td>
<td>4.62</td>
</tr>
</tbody>
</table>

Table 6 reveals the data for shear stress in the mixing section as a function of N and Q/N. Higher Intercept value for narrow K.B mixing section implies that the average of the shear stress value across the CCD grid is higher for the narrow K.B compared to wider K.B. Q/N has a more significant effect on shear stress compared to N, based on the higher coefficient values for Q/N compared to N. Higher coefficient for N for the narrow K.B mixing section implies that the change in shear stress is higher for the change in N variable, for the narrow K.B compared to wider K.B. The coefficient for Q/N is almost similar for wide and narrow K.B which implies that the change in Q/N variable produces similar changes in shear stress for both the screw geometries.

**Number of Revolutions in the Mixing Section**

Number of revolutions in the mixing section has always been a metric to understand the path taken by the polymer melt in the mixing section, when the operating conditions and screw geometry is changed. The number of revolutions are calculated from the following equation:

\[ R_{\text{mix}} = t_{\text{mix}} \times N \]  

Where, \( t_{\text{mix}} \) is the residence time output for the mixing section in the extruder, based on the Ludovic simulations.

\( R_{\text{mix}} \) calculations can be seen in Figure 11 for each of the operating conditions on the CCD grid.

Figure 11: Number of Revolutions for 24mm Narrow and Wide Mixing Section

Figure 11 reveals the data for the \( R_{\text{mix}} \) for all the operating conditions on the CCD grid. At constant Q/N, \( R_{\text{mix}} \) is almost constant as N increases which implies that the polymer melt follows the same path in the extruder at constant specific throughput. At constant N, increase in Q/N leads to a decrease in the number of revolutions taken by the polymer melt in the extruder to get across the mixing section. The polymer melt takes higher number of revolutions to get past the mixing section, compared to the narrow K.B mixing section.

**Conclusion**

The Residence Stress Distribution approach has been used to determine the dispersive mixing behavior of LDPE, for a set of operating conditions, chosen based on the Central Composite Design approach, on a 18mm Co-Rotating Twin Screw Extruder. The experimental data for %BU reveal that the %BU increases with increase in screw speed and specific throughput. Wider Kneading Blocks leads to a higher %BU of CAMES beads, which can be attributed to the fact that wider paddles are better dispersive mixing agents compared to Narrow Kneading Blocks.

The experimental data obtained, was further analyzed by performing computer simulations for the same screw configuration and operating conditions, using a 1-Dimensional Twin Screw Extrusion software called Ludovic. Several parameters related to twin screw extrusion such as the temperature, pressure, viscosity, shear rate, shear stress exhibited by the polymer melt, were simulated using Ludovic. An increase in screw speed increases the temperature of the polymer melt due to the heat generated because of friction between the barrel wall and the screw, and an increase in temperature leads to a decrease in viscosity (exponentially decreases with temperature). An increase in specific throughput leads to a decrease in temperature and eventually the viscosity increases. Shear rate is defined by the relation seen in Eq. 2 which implies that shear rate varies with the screw speed and the base diameter of the screw, which is constant for both the screw geometries. This causes the shear rate to vary with screw speed and remain constant for varying specific throughput. %BU is dependent on both the shear stress as well as the extensional shear stress. Based on the results obtained for the shear stress, it is known that an increase in both N and Q/N, or increase in N at constant Q/N, or increase in Q/N at constant N, leads to an increase in shear stress values that increases the percent break up, as there is more stress generated on the polymer melt, which might cause the CAMES beads to rupture beyond a specific limit. Shear stress decreases slightly for wider K.B which opposes the %BU results which increases with a change in the screw geometry (narrow to wide). This might be due to the fact that shear stress is not the dominating term that determines the %BU and there might be a significant effect of extensional stress on the polymer melt that might affect the percent break up values to a greater extent.
Similarly, the assumptions made on the RRD and RVD approach, that the polymer melt travels along the same path in the extruder, at a constant specific throughput, irrespective of the screw speed, have been validated using the simulations performed by Ludovic on $R_{\text{mix}}$, which can be found in the results section.

**References**


**Figure 12**: Screw Configuration for Narrow 24mm Mixing Section

**Figure 13**: Screw Configuration for Wide 24mm Mixing Section