Characterizing Granular Mixing Homogeneity at Various Dimensionless Mixing Lengths in a Double Screw Mixer

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Abstract
Granular mixing processes are commonly used to increase product homogeneity in many industrial applications involving pharmaceuticals, food processing, and energy conversion. Determining the appropriate granular mixing length is necessary to avoid over/under mixing and unnecessary power consumption. The goal of this study is to experimentally characterize the granular mixing process and determine, under various operating conditions, the needed mixing length to achieve adequate mixing in a laboratory-scale double screw mixer. Nine different combinations of screw rotation speeds and dimensionless screw pitches are used to investigate the rate of mixing at dimensionless mixing lengths of $L/D = 2, 5,$ and $10$. Composition and statistical analysis methods are employed to assess mixing effectiveness, and it is determined that the dimensionless mixing length is the most influential parameter in terms increasing granular homogeneity. For all the conditions tested, the granular mixture approaches an acceptable level of mixing for all testing conditions when the dimensionless mixing length is $L/D = 10$. However, the segregation rate throughout the screw mixer is vastly different for various combinations of screw rotation speed and dimensionless screw pitch, and is partly attributed to the influence of entrance effects caused by the material injection process.

Disciplines
Applied Mechanics | Electro-Mechanical Systems

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CHARACTERIZING GRANULAR MIXING HOMOGENEITY AT VARIOUS DIMENSIONLESS MIXING LENGTHS IN A DOUBLE SCREW MIXER

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ABSTRACT

Granular mixing processes are commonly used to increase product homogeneity in many industrial applications involving pharmaceuticals, food processing, and energy conversion. Determining the appropriate granular mixing length is necessary to avoid over/under mixing and unnecessary power consumption. The goal of this study is to experimentally characterize the granular mixing process and determine, under various operating conditions, the needed mixing length to achieve adequate mixing in a laboratory-scale double screw mixer. Nine different combinations of screw rotation speeds and dimensionless screw pitches are used to investigate the rate of mixing at dimensionless mixing lengths of L/D = 2, 5, and 10. Composition and statistical analysis methods are employed to assess mixing effectiveness, and it is determined that the dimensionless mixing length is the most influential parameter in terms increasing granular homogeneity. For all the conditions tested, the granular mixture approaches an acceptable level of mixing for all testing conditions when the dimensionless mixing length is L/D = 10. However, the segregation rate throughout the screw mixer is vastly different for various combinations of screw rotation speed and dimensionless screw pitch, and is partly attributed to the influence of entrance effects caused by the material injection process.

Keywords: Granular mixing, homogeneity, mixing length, screw mixer.

INTRODUCTION

Granular mixing processes are found in a large number of industries including chemical, pharmaceutical, plastics, food and mineral processing, and renewable energy, to name a few. Most commonly, granular mixing processes seek a high degree of homogeneity and in many cases can influence chemical reactions and heat and/or mass transfer rates [1]. Recently, significant effort has been directed towards characterizing granular flows involving non-spherical particles [2-4]. However, when mixer geometry is complex, computation models often fall short of accurately predicting granular mixing processes [5], resulting in the need for experimental methods.

Previous research efforts involving the mixing of biomass particles with inert heat carrier particles for the thermochemical conversion industry have indicated that the operating conditions and material residence time of biomass particles significantly influenced the trade-off between bio-oil and bio-char production [6, 7]. Therefore, accurate control of material residence time is needed to achieve high product yields. However, inappropriately designing the mixing geometry, more specifically the mixer length, and controlling the material residence time by solely changing the operating conditions of the mixer equipment (e.g., impeller rotation speed) can result in undesired characteristics, such as increased power consumption.
and mechanical wear. Careful consideration must be given to the mixing equipment’s design such that under/over mixing is avoided. Therefore, determining the optimal mixing length needed for adequate mixing in continuous mixing processes while still allowing for variability in material residence time is needed; this will minimize under/over mixing, power consumption, and equipment costs.

The goal of this study is to characterize the granular mixing process and determine the necessary dimensionless mixing length needed to achieve adequate mixing in a double screw mixer under various operating conditions. Given the mixing characteristics of common convective granular mixing devices reported in the literature [8], it is expected that: (i) the heterogeneity of the granular mixture would experience an asymptotic reduction as the dimensionless mixing length increased and (ii) the rate of mixing would depend on the operating conditions of the screw mixer. These two expectations will be tested in this study.

EXPERIMENTAL PROCEDURES

Screw Mixer

Granular mixing studies were conducted in the laboratory-scale double screw mixer shown in Figure 1. The screw mixer features two intermeshing noncontact screws with a screw diameter of D = 2.54 cm. One left hand and one right hand threaded screw were used to produce a screw rotation orientation of counter-rotating down-pumping, which was maintained for all experimental tests. Down-pumping refers to the direction of the material flow between the two screws. Kingston and Heindel [9] previously determined that the selection of this parameter was the most influential in terms of maximizing the mixing effectiveness of the screw mixer, and was therefore held constant in this study.

Three different screw mixer housings were designed and constructed, as shown in Figure 2, using a rapid prototype machining processes. The housings provided dimensionless mixing lengths of L/D = 2, 5, and 10, respectively, where L is the effective mixing length and D is the screw diameter. The effective mixing length is measured from the centerline of the downstream injection port (port two) to the beginning of the outlets ports in the bottom of the housing. The outlet ports were specifically designed to spatially divide the entire granular flow exit stream into four outlet ports that span in the horizontal direction, allowing the composition variance, $s^2$, to be computed. Additional details related to the screw mixer design, including the outlet port geometry, can be found in Kingston and Heindel [10].

Nine different operating conditions resulting from the nine combinations of screw rotation speeds at levels of $\omega = 20, 40,$ and 60 rpm and dimensionless screw pitch at levels of $p/D = 0.75, 1.25,$ and 1.75, where p is the screw pitch and D is the screw diameter, were tested in this study. By testing the influence of the dimensionless mixing lengths on the composition variance at different operating conditions, the rate of mixing for these operating conditions could be determined. A randomized full-factorial design of experiments for the 27 different combinations of parameters ($3 \times 3 \times 3 = 27$) was used. Three tests were performed at each of the 27 combinations of parameters thus totaling 81 tests that were performed in this study.

Granular Materials

A binary mixture of red oak chips and glass beads, as shown in Figure 3, were mechanically mixed inside the screw mixer. The red oak chips resemble a needle-like shape with large aspect ratios on the order of 6:1, and have a particle size
ranging from 500 to 6350 \( \mu m \) and an average true density, measured with a pycnometer, of 1350 kg m\(^{-3} \). The glass beads are spherical and have a particle size ranging from 300 to 500 \( \mu m \) and a true density of 2510 kg m\(^{-3} \). Red oak chips and glass beads were chosen because of their similar material properties to that of biomass and heat carrier media, respectively, which are used in the biomass thermochemical conversion industry. Because the granular materials differ in size, shape, and density, they are subject to percolation and buoyance forces which ultimately lead to segregation. The granular materials are metered into the screw mixer by two independent Tecweigh CR5 volumetric auger feeders. The granular materials are conveyed horizontally by the volumetric feeders, and then free-fall through a vertical injection tube into the screw mixer’s material injection ports. A material injection configuration which featured the red oak chips and glass beads being injected into port one and two, respectively, was maintained for all test conditions per the recommendations made by Kingston and Heindel [9]. Other parameters which were held constant include a 65% total volumetric fill ratio and a 10:1 glass beads to red oak chips mass flow rate ratio, resulting in a theoretical mixture composition in terms of glass bead mass fraction of \( x = 0.91 \). The selection of these parameters are based on recommendations by researchers in screw conveying applications [11] and typical operating conditions in the biomass thermochemical conversion industry.

![FIGURE 3: MAGNIFIED IMAGES OF (a) 500-6350 mm RED OAK CHIPS AND (b) 300-500 mm GLASS BEADS.](image)

**Composition Analysis**

The evaluation of granular mixing processes often involves the collection and composition analysis of samples. The methods outlined by Kingston and Heindel [10, 12] were used to determine the composition of the individually collected samples and compute the mass weighted composition variance, \( s^2 \):

\[
s^2 = \frac{\sum_{i=1}^{N} m_i \left( x_i - \overline{x} \right)^2}{\left( \frac{N-1}{N} \right) \sum_{i=1}^{N} m_i}
\]

where \( n \) is the number of the \( i^{th} \) sample, \( m_i \) is the mass of the \( i^{th} \) sample, \( x_i \) is the mass weighted composition of the \( i^{th} \) sample, \( \overline{x}_w \) is the mass weighted mean composition of the samples, and \( N \) is the total number of samples. In this study, the number of samples used to compute the composition variance is four, corresponding to the four samples that were collected from the outlet ports.

These methods evaluate the mixing effectiveness of the screw mixer by measuring the spatial heterogeneity from the four outlet ports, which divide the entire granular flow exit stream into separate channels across the exit. A composition variance equal to zero corresponds to a homogeneous mixture (within the ability to detect spatial differences using these methods), and represents the best-case scenario. As the magnitude of the composition variance increases, the mixing process effectively worsens, and the mixture becomes more segregated. Note that this procedure allows segregation quantification between the screw mixer’s outlet ports, but segregation within the individual outlet ports is not quantified.

**Statistical Analysis**

After performing the composition analysis, statistical analysis methods are used to relate the composition variance to the different dimensionless mixing lengths and operating conditions, allowing the most influential parameters to be determined. The model equation which was fitted to the experimental data and corresponds to the design of experiments used in this study is:

\[
y_{ijkl} = \mu + \alpha_i + \beta_j + \delta_k + \gamma_{ij}^{12} + \gamma_{ik}^{13} + \gamma_{jk}^{23} + \gamma_{ijk}^{123} + \epsilon_{ijkl}
\]

where \( y_{ijkl} \) is the measured response variable (i.e., composition variance); \( \mu \) is the mean response averaged over all levels of all parameters; \( \alpha_i \), \( \beta_j \), and \( \delta_k \) are the effects of the main-effect parameters (i.e., screw rotation speed, dimensionless screw pitch, and dimensionless mixing length); \( \gamma_{ij}^{12} \), \( \gamma_{ik}^{13} \), and \( \gamma_{jk}^{23} \) are the two-way interaction effects; \( \gamma_{ijk}^{123} \) is the three-way interaction effect; and \( \epsilon_{ijkl} \) is the random deviation from the true treatment mean [13]. Three tests were performed at each of the 27 combinations of parameters; thus “el” ranges from one to L, where \( L = 3 \).

To determine the significance of the seven terms in the model equation, seven hypotheses were tested, one for each of the terms listed above. However only the first two and the last hypothesis are shown here:
$H_{0,1} : \alpha_i = \ldots = \alpha_I = 0 \quad \text{versus} \quad H_{a,1} : \text{at least one } \alpha_i \neq 0$

$H_{0,2} : \beta_j = \ldots = \beta_J = 0 \quad \text{versus} \quad H_{a,2} : \text{at least one } \beta_j \neq 0$

$\ldots$

$H_{0,123} : \gamma_{ijk}^{123} = 0 \quad \text{for all } i, j, k \quad \text{versus} \quad H_{a,123} : \text{at least one } \gamma_{ijk}^{123} \neq 0$

where $I, J, K$ are the parametric levels one through three [13]. The F-test statistic and its corresponding p-value are used to determine if the null hypotheses failed to be rejected or were rejected in favor of the alternative hypotheses at an alpha level of 0.05.

RESULTS AND DISCUSSION

Previous studies by Kingston and Heindel [9] focused on performing optical visualization of the dynamic granular mixing process inside the screw mixer. Four cameras were used to capture the mixing process from the left, top, right, and bottom projections. A static image taken from the dynamic mixing process is shown in Figure 4. The four different projections (i.e., left, top, right, and bottom) are spatially aligned and temporally synced. The red oak chips appear brown and the glass beads appear gray. The granular materials are injected into the material injection ports shown on the left side of the image, and are mechanically mixed and conveyed from left to right before exiting the screw mixer through the four outlet ports in the bottom of the screw mixer. The operating condition of the screw mixer shown in Figure 4 are a screw rotation speed of $\omega = 60$ rpm, a dimensionless screw pitch of $p/D = 0.75$, and a dimensionless mixing length of $L/D = 10$.

These previous studies by Kingston and Heindel [9] only focused on capturing mixing videos for a screw mixer with a dimensionless mixing length of $L/D = 10$, therefore shorter dimensionless mixing lengths are not available. However, the approximate location of the outlet ports for dimensionless mixing lengths of $L/D = 2$ and $5$ as shown in Figure 4.

ANOVA

The key parameters of the statistical analysis are summarized in the ANOVA table shown in Table 1, where the degrees of freedom are symbolized by df, the sum of squares by SS, the mean square by MS, and the F-test statistic by F. For the terms to be declared statistically significant, their corresponding p-value must be less than the alpha level of 0.05. As shown, six of the seven terms are statistically significant, with only the main-effect term associated with the screw rotation speed being declared not significant. The model equation had a coefficient of determination of $R^2 = 0.948$. As indicated by their respective p-values, all of the terms in the model equation were determined to be statistically significant, except for the main-effect term associated with the screw rotation speed. Furthermore, the three-way interaction term was determined to be statistically significant, thus it must be further investigated for an indication into the effect that each of the levels of parameters have on the composition variance. From the ANOVA results shown in Table 1, it is obvious that the dimensionless mixing length had the most influence on the granular mixing process because of its high F value (130.10) and corresponding low p-value ($< 0.001$).

The dimensionless screw pitch was the second most influential parameter with an F value of 70.82 and a p-value of $< 0.001$, and when combined with the dimensionless mixing length, these two parameters produced the most influential two-way interaction term which yielded an F value of 116.56 and a p-value of $< 0.001$. However, in order to identify which levels of parameters produce the most desirable operating conditions, the three-way interaction term must be visualized because it is the highest order statistically significant term.

![FIGURE 4: SNAPSHOT OF THE DYNAMIC MIXING PROCESS INSIDE THE SCREW MIXER WITH A DIMENSIONLESS SCREW PITCH OF p/D = 0.75 [9].](http://proceedings.asmedigitalcollection.asme.org/)

<table>
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<tr>
<th>Source</th>
<th>df</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>p-value</th>
<th>Significant</th>
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<tr>
<td>Screw Rotation Speed</td>
<td>2</td>
<td>2.10E+3</td>
<td>1.05E+2</td>
<td>2.87</td>
<td>0.065</td>
<td>N</td>
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<tr>
<td>Dimensionless Screw Pitch</td>
<td>2</td>
<td>5.12E+3</td>
<td>2.56E+2</td>
<td>70.82</td>
<td>&lt; 0.001</td>
<td>Y</td>
</tr>
<tr>
<td>Dimensionless Mixing Length</td>
<td>2</td>
<td>9.41E+4</td>
<td>4.71E+2</td>
<td>130.10</td>
<td>&lt; 0.001</td>
<td>Y</td>
</tr>
<tr>
<td>Screw Rotation Speed</td>
<td>4</td>
<td>1.53E+6</td>
<td>3.82E+3</td>
<td>16.55</td>
<td>&lt; 0.001</td>
<td>Y</td>
</tr>
<tr>
<td>Dimensionless Screw Pitch</td>
<td>4</td>
<td>1.34E+6</td>
<td>3.34E+2</td>
<td>9.25</td>
<td>&lt; 0.001</td>
<td>Y</td>
</tr>
<tr>
<td>Dimensionless Mixing Length</td>
<td>4</td>
<td>1.69E+5</td>
<td>4.22E+2</td>
<td>116.56</td>
<td>&lt; 0.001</td>
<td>Y</td>
</tr>
<tr>
<td>Screw Rotation Speed</td>
<td>8</td>
<td>9.20E+5</td>
<td>1.14E+3</td>
<td>2.16</td>
<td>0.005</td>
<td>Y</td>
</tr>
<tr>
<td>Error</td>
<td>54</td>
<td>1.95E+6</td>
<td>3.62E+3</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Total</td>
<td>80</td>
<td>3.73E+6</td>
<td></td>
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</table>
Visualizing Parametric Interactions

The three-way interaction term is shown graphically in Figure 5, and provides critical information relating the various levels of each parameter to its influence on the composition variance. For convenience, an averaging line was added to each of the nine plots to help identify trends. The nine plots correspond to the nine different operating conditions resulting from all the possible combinations of screw rotation speed and dimensionless screw pitch. Plotted on the left vertical axis is the composition variance, $s^2$. The top and bottom horizontal axes display the dimensionless screw pitch, $p/D$, and the dimensionless mixing length, $L/D$, respectively. The screw rotation speed, $\omega$, is plotted on the right vertical axis. The three data points at each dimensionless mixing length for each operating condition correspond to the three tests that were performed. A high degree of repeatability was present, as indicated by the small variance (not to be confused with the composition variance) within the three tests.

The small magnitude of the composition variance shown in Figure 5 is a result of the composition variance being determined from the mixture composition, which ranges from zero to one. For example, one test which resulted in a composition variance of $s^2 = 0.0021$ corresponded to a glass bead mass fraction ranging from $x = 0.84$ to 0.93, for the four outlet ports. Meanwhile, a composition variance of $s^2 = 0.0006$ corresponded to glass bead mass fraction ranging from $x = 0.87$ to 0.92. Recall that a composition variance of zero corresponds to a homogeneous mixture (i.e., the mixture composition for each outlet port would be identical) and is the desired state of mixing.

Uncertainty Analysis

An uncertainty analysis was performed to quantify the error associated with the composition variance using Taylor’s series expansion propagation of error procedure [14]. Overall, the uncertainty in the composition variance, $U_{s^2}$, ranged from 1 to 5% of the composition variance, $s^2$, and is shown in Figure 5 by vertical error bars overlaid on the data points; all error bars fall within the circular symbols. This error is only associated with the determination of the composition variance and is not associated with the variance within the parameters themselves, which is shown graphically by the spread of the three tests, and was quantified using the prescribed ANOVA methods.

Interpreting Parametric Interactions

Before interpreting the parametric interactions, it is important to mention that when the granular materials are injected into the screw mixer, the larger, less dense red oak particles are injected into port one, and the smaller, denser glass beads are injected into port two. This configuration was chosen because the granular materials would be positioned in such a way that it would induce a natural mixing process caused by percolation and buoyant forces, as noted by Kingston and Heindel [9]. Thus, there essentially exists an entrance region “boundary condition” which features a relatively low composition variance at short mixing lengths. The granular material experiences changes in its flow structures and mixing process due to the entrance/exit of the material upstream/downstream of the point of interest. Because the material experiences minimal mixing near these boundary conditions, the actual “mixing length” of the screw mixer is effectively shortened. Thus, instead of sampling the mixture at $L/D = 10$, for example, it is effectively being sampled slightly upstream from this location. This behavior does not appear to have any influence on the mixing quantification results because the selection of the sampling location, in terms of the dimensionless mixing length, is arbitrary.

These effects were noted in previous studies by Kingston and Heindel [9] which featured the visualization of the dynamic mixing process from the entire screw mixer’s periphery. As a result, these effects must be taken into consideration when interpreting the results of this study in order to fully understand the granular mixing behavior.

The following three sections separate the three different levels of the dimensionless screw pitch, and consider the effects of the screw rotation speed and dimensionless mixing length within each section. Comparisons between different levels of
dimensionless screw pitch are then explicitly compared. This presentation methodology is utilized because of the vastly different results found at each of the dimensionless screw pitches, as shown in Figure 5.

**Dimensionless Screw Pitch of p/D = 0.75**

First consider the response of the composition variance versus the dimensionless mixing length at the three levels of the screw rotation speed, while holding the dimensionless screw pitch constant at p/D = 0.75. As shown in Figure 5, there appears to be an asymptotic reduction in the composition variance as the dimensionless mixing length increases and this trend remains fairly consistent for all three screw rotation speeds. For example, for a screw rotation speed of \( \omega = 20 \) rpm, the composition variance is approximately equal to 0.0018 at L/D = 2, and then reduces by approximately 50% to about 0.0009 at L/D = 5, and then is further reduced by approximately 50% to approximately 0.0005 at L/D = 10. This result confirms part one of the aforementioned expectations, at least for a dimensionless screw pitch of p/D = 0.75, that there is an asymptotic reduction in the composition variance as the dimensionless mixing length increases.

Despite similar trends, the magnitude of the composition variance in the first half of the screw mixer (i.e., before L/D = 5) varies as the screw rotation speed varies, and is significantly lower for \( \omega = 40 \) rpm \( (s^2 = 0.0010) \) than it is for \( \omega = 20 \) and 60 rpm \( (s^2 = 0.0018 \) and 0.0022, respectively). However, the differences in the composition variance at L/D = 2 are minimized as the granular material moves through the screw mixer and approaches L/D = 5 and 10 because all three levels of the screw rotation speed now exhibit nearly identical composition variances of approximately \( s^2 = 0.0008 \) and 0.0005, respectively. This difference is a clear indication into why the statistical analysis indicated that the screw rotation speed is one of the three significant parameters in the three-way interaction term.

The dimensionless screw pitch of p/D = 0.75 features a screw flighting profile which is primarily perpendicular to the axial flow direction, as shown in Figure 4. Furthermore, there are a relatively large number of screws flights in a short distance. The previously noted entrance effects are unable to propagate into the screw mixer very far because of these two geometric constraints, and may be on the order of one dimensionless mixing length \( (L/D = 0.5) \). This causes segregation to take place at relatively short mixing lengths, and is the reason for the large composition variance at L/D = 2.

**Dimensionless Screw Pitch of p/D = 1.25**

Unlike the continuous reduction in composition variance as a function of dimensionless mixing length shown for p/D = 0.75, the dimensionless screw pitch of p/D = 1.25 shows vastly different behavior. As shown in Figure 5, the granular material indicates minimal segregation at L/D = 2 and 10, but a large increase in composition variance occurs at L/D = 5, indicating a high degree of segregation. Initially, it was thought to be user error during the sample collection and/or analysis process. Thus, three additional independent tests were conducted at dimensionless mixing lengths of L/D = 2 and 5 for a dimensionless screw pitch of p/D = 1.25; totaling 6 tests (3 original + 3 repeated = 6) at each of these conditions. However, after analyzing and plotting the additional tests, the new data points were essentially overlaid on the old data points and displayed a high degree of reproducibility; eliminating the likelihood for user error and confirming the trends shown in Figure 5.

The shape of the screw flight profile for a screw which features a dimensionless screw pitch of p/D = 1.25 is slightly rotated such that it offers less restriction in the axial direction, and has fewer screw flights in the same axial distance relative to the dimensionless screw pitch of p/D = 0.75. This change in screw geometry is illustrated in Figure 6. As a result, when the granular materials enter the screw mixer with a dimensionless screw pitch of p/D = 1.25, they almost instantaneously begin to leave the screw mixer when the outlet ports are positioned at L/D = 2. Therefore, segregation does not have adequate time to take place and the composition variance initially remains fairly low. In other words, by changing the dimensionless screw pitch from p/D = 0.75 to 1.25, the entrance effects are being prolonged a further distance into the screw mixer.

As the dimensionless mixing length increases to L/D = 5, the material residence time increases and the granular mixture simultaneously segregates and mixes, with segregation taking place at a much higher rate causing the large increase in the composition variance. As the screw mixer continues to mix the two granular components together, it begins to break up the red oak agglomerations, causing the mixture to become more homogeneous and resulting in a reduction in the composition variance near L/D = 10, as shown on the right side of Figure 6.

The effect of the screw rotation speed does not have a significant influence on the mixing effectiveness at a dimensionless screw pitch of p/D = 1.25. This is shown by the relatively unchanged results shown in Figure 5.

**Dimensionless Screw Pitch of p/D = 1.75**

As part two of the study expectations stated, the rate of reduction in the heterogeneity of the granular material as a function of dimensionless mixing length is expected to depend on the operating conditions of the screw mixer. Therefore, it is not surprising that the behavior of the composition variance for the dimensionless screw pitch of p/D = 1.75 is vastly different than it is for either the p/D = 0.75 or 1.25 case. As shown in Figure 5, the magnitude of the composition variance at L/D = 2 for p/D = 1.75 is substantially lower than it is for p/D = 0.75, and approximately the same as the p/D = 1.25 case. This is once again a consequence of the entrance regions effects being prolonged in the screw mixer. As the granular materials begin to propagate through the screw mixer and reach L/D = 5, the composition variance is much lower than it is for either the p/D = 0.75 or 1.25 case because the longer dimensionless screw pitch offers an advantageous mixing process and produces a more homogeneous mixture, as shown in Figure 7. The mixing of the two granular materials continues and the composition variance reduces as the mixture exits the screw mixer at L/D = 10.

In this study, and previous studies [9, 10, 15], it has been shown that increasing the dimensionless screw pitch increased the mixing effectiveness in screw mixing applications.

Similar to the dimensionless screw pitch of p/D = 1.25, the screw rotation speed had a small, but slightly noticeable influence on the mixing effectiveness of the screw mixer for a dimensionless screw pitch of p/D = 1.75. In previous studies, Kingston and Heindel [9] noted that higher screw rotation speeds increased the mixing effectiveness; a result which is also shown in Figure 5 by the reduction in composition variance as the screw rotation speed increases from \( \omega = 20 \text{ rpm} \) to \( \omega = 60 \text{ rpm} \). However, only a slight reduction in the composition variance is observed as the screw rotation speed increases.

This independence from the screw rotation speed coupled with its relatively low composition variance is why this geometrical configuration (p/D = 1.75) offers a mixing process which will produce more adequate mixing in a much shorter mixing length (and consequently less time), than the other conditions. A favorable result as this will minimize power input and equipment costs.

**FIGURE 7: SNAPSHOT OF THE DYNAMIC MIXING PROCESS INSIDE THE SCREW MIXER WITH A DIMENSIONLESS SCREW PITCH OF p/D = 1.75 [9].**

**CONCLUSIONS**

Overall, the granular mixture approaches an acceptable level of homogeneity as the dimensionless mixing length nears L/D = 10 for all nine operating conditions, as shown in Figure 5. The screw rotation speed had a moderate influence on the mixing process at a dimensionless screw pitch of p/D = 0.75, but a minimal influence at p/D = 1.25 and 1.75. However, the dimensionless screw pitch had a dramatic influence on two major items: (i) the distance that the entrance effects were able to propagate into the screw mixer, and (ii) the mixing effectiveness of the screw mixer. A screw rotation speed of \( \omega = 60 \text{ rpm} \) and a dimensionless screw pitch of p/D = 1.75 reduced the degree of heterogeneity within the granular mixture and was found to be relatively independent of the dimensionless mixing length. This operating condition represents the optimal operating condition for the parameters considered in this study, and allows the user to make design decisions based on material residence time considerations and not based on mixing effectiveness.

To fully confirm the conclusions that increasing the dimensionless screw pitch allows the entrance effects to penetrate further into the screw mixer, addition tests should be conducted. These tests would need to sample the granular material with finer resolution in terms of the dimensionless mixing lengths, perhaps on the order of L/D = 1 across the
entire screw mixer length. By only sampling the granular mixture at three axial locations used in this study, the influence of the entrance effects can only by proposed, and cannot be confirmed. However, performing these additional tests would require the construction of a series of mixers or a mixer with a variable sampling location; resulting in additional equipment costs. Obviously, this reinforces the need for the development of more accurate granular mixing computation models.

ACKNOWLEDGMENTS

Support for portions of the work presented in this paper from Phillips 66 Company is acknowledged.

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