Visualization and Composition Analysis to Quantify Mixing in a Screw Pyrolyzer

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Abstract
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Keywords
Composition analysis, granular mixing, optical visualization, screw pyrolyzer

Disciplines
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ABSTRACT

Characterizing the mixing effectiveness of systems or processes in granular applications is difficult due to ineffective sampling procedures and a lack of quantifiable measurement techniques. The mixing effectiveness of a screw pyrolyzer consisting of a binary mixture of 500 – 6350 µm red oak chips and 300 – 500 µm glass beads is evaluated using optical visualization and composition analysis techniques. The mass fraction of binary mixture samples is determined and the weighted sample variance from four outlet ports is used to evaluate the mixing effectiveness. The effect of dimensionless screw pitch on the mixing effectiveness is investigated at levels of p/D = 0.75, 1.25, and 1.75. Optical visualization is captured across the entire mixing region’s periphery allowing qualitative observations to be made, leading to the visual observation that increasing the dimensionless screw pitch increases the mixing effectiveness. Quantitative composition analysis utilizing a one-way analysis of variance (ANOVA) statistical model confirms that increasing the dimensionless screw pitch from 0.75 to 1.25 results in a significant increase in mixing effectiveness. However, diminishing increases in mixing effectiveness were shown as the dimensionless screw pitch increased from 1.25 to 1.75, and statistically these two conditions could not be distinguished given the amount of data in this study. Results are compared to previous granular mixing measurement techniques found in the literature, and similar results are reported.

Keywords: Composition analysis, granular mixing, optical visualization, screw pyrolyzer.

INTRODUCTION

The mixing of granular materials has a significant influence on the yield and/or quality of the desired products in numerous industrial processes including energy generation, concrete manufacturing, food processing, and pharmaceutical production. For example, screw pyrolyzers being developed for the thermochemical conversion of biomass into bio-oil. The screw pyrolyzer’s high heat transfer rates and resulting bio-oil yields are significantly influenced by the screw pyrolyzer’s operating conditions and its ability to mechanically mix high density inert heat carrier media (e.g., stainless steel shot, refractory sand, etc.) with low density biomass particles (e.g., red oak chips, ground corn cobs, switchgrass, etc.).

The purpose of a mixing operation is that it produces a mixture with an internal structure of acceptable quality [1]. Mixing processes for granular materials often seek a high degree of homogeneity, and in some instances, the purpose is to effect simultaneous processing, such as chemical reactions [1]. Despite the solids-handling industry being quite mature, the design and operating conditions of equipment remains open to speculation and lacks quantitative justification [1]. The methods used to determine granular mixing effectiveness is limited [2]. Moreover, process design and operation are very difficult, being largely based on trial-and-error rather than science [1].
An important and fundamental problem for mixing of granular materials is the tendency for mixtures to segregate due to small differences in either particle size or density [3]. A considerably large number of factors can influence this mixing process. Vanarase and Muzzio [4] researched the effect of operating conditions and design parameters in a continuous horizontally orientated impeller powder mixer and found that intermediate rotation rates optimized the overall mixing effectiveness.

The effect of screw pitch has been shown to be a critical factor in the powder industry. Uchida and Okamoto [5] used an X-ray system coupled with a 2D imaging device to track powder flows in a single screw feeder. Small amounts of tungsten tracer powder were injected and tracked as they moved downstream. Uchida and Okamoto [6] later used this imaging system to measure the diffusion coefficient (a measure of mixing effectiveness) of four screw designs each having a 25 mm diameter. Three screws featured a single flighting design with screw pitches of 25, 37.5, and 57.5 mm while the fourth screw featured a double flighting design with a screw pitch of 25 mm, as shown in Figure 1.

The diffusion coefficient was determined to be the largest for the 57.5 mm pitch screw. Uchida and Okamoto concluded that increasing the screw pitch increased the diffusion coefficient and increased the frequency of the path line sine curve, as shown in Figure 2.

In the current study, the effect of dimensionless screw pitch on mixing effectiveness is investigated in a double screw cold-flow pyrolyzer, which acts as a screw mixer. Optical visualization of the entire mixing length and periphery (i.e., 360°) was completed for qualitative mixing assessment. Samples from four different exit ports were collected and analyzed for quantitative mixing assessment.

EXPERIMENTAL SETUP

A laboratory-scale double screw cold-flow pyrolyzer was designed and constructed for granular mixing studies, as shown in Figure 3. The pyrolyzer housing was fabricated from a transparent plastic material using a rapid prototype machining process (i.e., 3D printer) allowing 360° optical access to the mixing region thus enabling optical visualization to be performed. The remaining parts were fabricated from opaque plastic material using the same machining process.

The pyrolyzer features two parallel and horizontally mounted intermeshing noncontact screws. The screw outside diameter, D, was chosen as the characteristic length for the system. The effect of dimensionless screw pitch (p/D) on the mixing effectiveness was investigated for p/D = 0.75, 1.25, and 1.75, as shown in Figure 4.

The screws rotate inside a clear, contoured housing and are driven by a variable speed gearmotor through a set of specifically designed spur gears. A 40 rpm screw rotation speed and co-rotating screw rotation orientation was maintained for all mixing studies.
Two injection ports are positioned in the top of the housing halfway between the screws and are axially located two screw diameters apart from one another. Four uniquely designed outlet ports in the bottom of the pyrolyzer housing horizontally divide the granular flow into four separate channels, as shown in Figure 5. The arrows illustrate the direction of the material flow and the numbers illustrate the port numbering convention. The granular materials exit the pyrolyzer from the bottom and free-fall to the collection basin. The effective mixing length, measured from the centerline of the downstream injection port (port two) to the beginning of the outlet ports provides a length-to-screw diameter ratio of \( L/D = 10 \).

A 65% volumetric fill is recommended in screw conveyor applications \[7\] and was maintained for all experimental tests by selecting the appropriate injection mass flow rate for each dimensionless screw pitch, as shown in Table 1. A 10:1 glass bead to red oak mass flow rate ratio was maintained for all tests. The volumetric feeders were calibrated to yield the desired mass flow rates.

### Table 1: Red Oak and Glass Bead Mass Flow Rates Required to Maintain a 65% Volumetric Fill.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Dimensionless Screw Pitch (( p/D )) [-]</th>
<th>Red Oak Mass Flow Rate [kg/hr]</th>
<th>Glass Bead Mass Flow Rate [kg/hr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.75</td>
<td>2.0</td>
<td>20.0</td>
</tr>
<tr>
<td>2</td>
<td>1.25</td>
<td>3.5</td>
<td>35.0</td>
</tr>
<tr>
<td>3</td>
<td>1.75</td>
<td>4.0</td>
<td>40.0</td>
</tr>
</tbody>
</table>

### EXPERIMENTAL METHODS

Two general techniques are available for characterizing mixing: (i) non-invasive methods enabling observations to be made without the need for sampling and (ii) invasive methods requiring material to be sampled and analyzed. Both techniques are presented in this study, and coupled together provide a thorough method to quantify mixing in a screw pyrolyzer.

#### Optical Visualization

Qualitative optical visualization of the dynamic granular mixing inside the pyrolyzer was captured from four projections (i.e., left, top, right, and bottom) simultaneously. Figure 7 illustrates the positioning of four high definition camcorders, the inlet and outlet tubes, and the screw pyrolyzer. The camcorders capture images at 60 frames per second with 1920 \( \times \) 1080 resolution. Figure 8 (a) and (b) illustrate the four projections from which visualization was captured and the
cropped projections with a typical path line of a particle being injected into port two, respectively.

FIGURE 7: OPTICAL VISUALIZATION EXPERIMENTAL SETUP

Temporal and spatial syncing was accomplished using Adobe Premiere Pro CS6. A specific event in each of the four independent videos was temporally synced; coupling them into one grouped video. The top and right projections were captured in the orientation shown in Figure 8 (a); however the left and bottom projections were spatially synced by inverting them about their vertical and horizontal axis, respectively. This enables the material to flow from left to right in all images and for screw one and two to be aligned in the top and bottom projections. The four projections were combined into a simple and compact interface by cropping everything outside the mixing region and labeling each projection, as shown in Figure 8 (b).

Sampling Procedure

Accurate sampling techniques have been a common problem for many researchers wanting to characterize powder and granular flows. Brown [8] attempted to perform preliminary cold-flow mixing studies by removing the top plate from a screw pyrolyzer designed for chemically reacting flows. The inability to collect samples at locations other than the top layer of material was noted. The unique design of the screw pyrolyzer’s dividing mechanism used in this study allowed the entire cross-sectional area of the granular flow to be sampled by directing it into the four separate outlet ports; thus eliminating traditional problematic sampling techniques.

The screw pyrolyzer was set-up with the desired dimensionless screw pitch and was allowed to reach steady state by running the granular materials through the system for a sufficiently long time period. A quick shut-off switch was triggered, simultaneously stopping the screws and volumetric feeders. Collection bags were placed at the end of outlet tubes before reactivating the pyrolyzer and feeders. The system was run for approximately 5 – 10 seconds until the sample collection bags reached a desired fill level. The system was shut-down and the collection bags were removed and sealed. The sampling process was then repeated for the remaining
trials. The sample size collected from the outlet ports was specifically determined such that the entire sample would fit in the measuring device (a pycnometer, which will be described in more detail in the following section). It was critical that the entire collected sample be analyzed because if only a portion were used, there would be no way of guaranteeing the composition of the analyzed portion would be identical to the collected sample.

**Composition Analysis**

The degree of homogeneity (or lack thereof) of the four samples collected from the outlet ports provided an indication of the screw pyrolyzer mixing effectiveness. Ideally, a homogenous mixture of red oak and glass beads would be present everywhere within the pyrolyzer. However, segregation resulting from particular operating conditions and differences in density and particle size may occur.

The mixing effectiveness of a process is commonly determined as a function of the mixture composition; however, much difficulty lies in measuring this material property. Quantitative characterization has most commonly relied on determining the spread of the composition, symbolized by the sample variance, $s^2$ [1].

For this study, the mixture composition was determined by developing a correlation between the mixture density and the glass bead mass fraction. Eleven mixtures of red oak and glass beads in 10% increments by mass ranging from 0% glass beads (100% red oak) to 100% glass beads (0% red oak) were used to develop a correlation between the glass bead mass fraction and the mixture density as shown in Figure 9. The mass of the mixtures was measured and the true volume of the mixtures was analyzed using a pycnometer, an instrument used to precisely measure the true volume of solids, from which the true mixture density was determined.

A least squares regression equation, shown in Eq. (1), was fitted to the experimental data and was used to determine each collected sample’s composition from the measured mixture density.

$$\rho_{\text{mixture}} = 6.23E^{-5} x_g^2 + 5.27E^{-3} x_g + 1.36 \quad (1)$$

The correlation exhibits an interesting phenomenon; the mixture density is nonlinear with respect to the composition. More specifically, the correlation corresponds to a harmonic mean, in contrast to a linear arithmetic mean. The theoretical harmonic mean equation consisting of a binary mixture of red oak and glass beads is:

$$\rho_{\text{mixture}} = \left(\frac{x_g \rho_{gb} + (1-x_g) \rho_{ro}}{\rho_{gb}}\right)^{-1} \quad (2)$$

where $\rho_{\text{mixture}}$ is the true mixture density measured by the pycnometer, $x_g$ is the glass bead mass fraction, and $\rho_{gb}$ and $\rho_{ro}$ are the individual densities of glass beads and red oak, respectively. The theoretical harmonic mean equation is illustrated in Figure 9 by the dashed line. Less than 2% relative error exists between the experimental data and the harmonic mean equation over the entire composition range.

**Statistical Analysis**

The response variable used for the statistical analysis is the glass bead mass fraction weighted variance between the four samples collected from each outlet port:

$$s^2 = \frac{\sum_i^N w_i (x_i - \bar{x}_w)^2}{(N-1)\sum_i^N w_i} \quad (3)$$

where $s^2$ is the glass bead mass fraction weighted variance, $N$ is the number of ports (four in this study), $w_i$ is the weight of the $i^{th}$ port sample, and $\bar{x}_w$ is the weighted mean mass fraction of all the sample ports. The weighted variance is dimensionless because the mass fraction is dimensionless and must be used instead of the variance because the mass flow rates through the four outlet ports are not necessarily equal. Ideally, the composition of the outlet ports would be identical, resulting in a weighted variance of zero (best degree of mixing). As the degree of mixing worsens, the weighted variance increases.

Three different treatments (i.e., dimensionless screw pitches) were tested and three observations were collected from each treatment, totaling nine trials. A one-way analysis of variance (ANOVA) statistical model was applied using JMP Pro 10 to compare the composition weighted variance to the treatments. The model equation is:

$$y_{ij} = \mu + \alpha_i + \varepsilon_{ij} \quad (4)$$
where \( y_{ij} \) is the measurement taken at the \( i^{th} \) treatment and the \( j^{th} \) observation, \( \mu \) is the average of all treatments, \( \alpha_i \) is the effect due to the \( i^{th} \) treatment, and \( \varepsilon_{ij} \) is the random deviation from the true treatment mean \([9]\).

Let \( \mu_i \) equal the true response when treatment \( i \) is applied and \( I \) equal the total number of treatments being compared. The null hypothesis is that the response variable (i.e., weighted variance) is equal for all treatments (i.e., \( H_0: \mu_1 = \mu_2 = \ldots = \mu_I \)). The alternative hypothesis is at least two of the treatments are different (i.e., \( H_A: \) at least two \( \mu_i \)’s are different). In other words, the alternative hypothesis suggests that the dimensionless screw pitch has an effect on the mixing effectiveness of the screw pyrolyzer. The f-test statistic is a ratio of the mean square between treatments to the mean square within treatments; also known as the ratio of the mean square for treatments to the mean square for error (i.e., \( f = \frac{\text{MSTr}}{\text{MSE}} \)). The test statistic is used to determine if the null hypothesis is true or rejected in favor of the alternative hypothesis, at an alpha level of 0.05.

If the prescribed null hypothesis is rejected in favor of the alternative hypothesis, at least two of the treatments are different. An additional analysis procedure is needed to conclude which of the three treatments differ; commonly referred to as a multiple comparisons procedure. Tukey’s [9] honestly significant difference (HSD) test procedure was used to make all possible comparisons between pairs of treatments. The null hypothesis is \( H_0: \mu_i - \mu_j = 0 \) where \( i \) and \( j \) represent the \( i^{th} \) and \( j^{th} \) treatment while the alternative hypothesis is \( H_A: \mu_i - \mu_j \neq 0 \); an alpha level of 0.05 was chosen. This procedure compares all possible treatment combinations.

**RESULTS AND DISCUSSION**

**Optical Visualization**

Figure 10 (a), (b), and (c) illustrate snapshots taken from movies of the dynamic mixing process that was captured using the prescribed optical visualization techniques for treatments one, two, and three; corresponding to dimensionless screw pitches of \( p/D = 0.75, 1.25, \) and 1.75, respectively. The red oak appears brown and the glass beads appear gray and are injected into port one and two, respectively, through the black polyethylene tubes shown in the top projection. The granular materials are conveyed from left to right and exit through the four outlet ports shown in the bottom projection.

The effect of increasing the dimensionless screw pitch on the mixing mechanics produced several important observations including: (i) the radial velocity of the granular material increased relative to the axially velocity, (ii) less adhesion was present between the screw flights and granular materials due to a decreased screw flighting surface area, (iii) a larger clearance gap between the intermeshing screws exists, (iv) the material residence time decreased, (v) variations in fill height between the screw flights became more apparent, (vi) the volumetric fill of the two screws were more similar, and (vii) the mixing effectiveness appeared to increase. The increase in radial velocity is directly related to the increase in the frequency of the path line sine curve observed by Uchida and Okamoto [6].

\[
\text{(a) TREATMENT 1: } p/D = 0.75
\]

\[
\text{(b) TREATMENT 2: } p/D = 1.25
\]

\[
\text{(c) TREATMENT 3: } p/D = 1.75
\]
Composition Analysis

Figure 11 illustrates the weighted variance as a function of the dimensionless screw pitch. The weighted variance decreases as the dimensionless screw pitch increases from $p/D = 0.75$ to $p/D = 1.25$; however, further increasing the dimensionless screw pitch to $p/D = 1.75$ appears to show diminishing effects on the weighted variance. The weighted variance and the mixing effectiveness are inversely proportional (i.e., a small weighted variance corresponds to a high mixing effectiveness).

As illustrated in Figure 11, the within-treatment variance (i.e., variance within the three observations at each dimensionless screw pitch) is small relative to the between-treatment variance (i.e., variance between the dimensionless screw pitches) when comparing the 0.75 dimensionless screw pitch to either the 1.25 or 1.75 dimensionless screw pitch. In contrast, the within-treatment and between-treatment variance between the 1.25 and 1.75 dimensionless screw pitches are more similar. The variance was quantified using the prescribed one-way ANOVA hypothesis; resulting in the ANOVA Table shown in Table 2, where SS is the sum of squares, df is the degrees of freedom, MS is the mean square, $f$ is the f-test statistic, and $p$-value is the probability of obtaining the measured test statistic [9]. The $p$-value (0.0002) is less than the alpha level (0.05) therefore the null hypothesis is rejected in favor of the alternative hypothesis; thus at least two of the treatment’s weighted variances are different (i.e., the dimensionless screw pitch has an effect on the weighted variance). To determine which treatments are significantly different, Tukey’s HSD procedure was applied [9] and resulted in $p$-values of 0.0007, 0.0003, and 0.482 when comparing treatments one and two, one and three, and two and three respectively. Consequently, a significant difference exits between treatments one and two and one and three, but not between treatments two and three because the within-treatment and between-treatment variances of treatments two and three are too similar.

<table>
<thead>
<tr>
<th>Source</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>$f$</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>$6.40E^7$</td>
<td>2</td>
<td>$3.20E^7$</td>
<td>45.7</td>
<td>0.0002</td>
</tr>
<tr>
<td>Error</td>
<td>$4.20E^6$</td>
<td>6</td>
<td>$7.01E^7$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$6.82E^7$</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The magnitude of the weighted variance, which is related to the degree of mixing (or segregation), can be significantly influenced by changing the granular materials being used. If the material density ratio (i.e., heat carrier media to biomass density ratio) was further increased, it is likely that the weighted magnitude of the weighted variance would increase due to enhanced segregation. In contrast, if the density ratio were to approach unity, segregation would likely be due only to differences in particle size and shape, and not density. Similar effects are expected if the particle sizes were to change. Increasing the difference in particle sizes between the biomass and heat carrier media would likely cause an increased weighted variance and worsen the mixing effectiveness.

The power of the statistical analysis procedure is heavily influenced by the number of observations. This study used a relatively small number of trials (nine). A more rigorous analysis procedure using more trials could possibly result in the ability to distinguish a difference between treatments two and three (i.e., 1.25 and 1.75 dimensionless screw pitches).

Similar results were found by Uchida and Okamoto [6] who concluded that the mixing effectiveness was enhanced by increasing the screw pitch. The results of this study confirm that the presented quantification technique is valid and consistent with previous literature results.

CONCLUSIONS

A unique visualization and composition analysis technique to quantify mixing in a screw pyrolyzer was presented. The optical visualization procedure produced several qualitative noteworthy observations which indicated that increasing the dimensionless screw pitch increased the mixing effectiveness. Composition analysis provided a quantitative measurement technique to determine the mixing effectiveness as a function of the dimensionless screw pitch and confirmed the qualitative observations. The mixing effectiveness of the screw pyrolyzer was related to the weighted variance of the composition from the four outlet ports. A smaller weighted variance corresponded to a higher mixing effectiveness.
significantly increased as the dimensionless screw pitch increased from $p/D = 0.75$ to $1.25$. However, diminishing increases in mixing effectiveness were shown as the dimensionless screw pitch increased from $1.25$ to $1.75$ and statistically these two treatments could not be distinguished given the amount of data used in this study. The qualitative optical visualization and quantitative composition analysis results were compared to previous granular mixing measurement techniques found in the literature, and similar results were reported.

Future studies will utilize this measurement technique to investigate a number of critical factors that could contribute to the screw pyrolyzer’s mixing effectiveness (e.g., screw rotation speed, injection port configuration, etc.).

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