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Optical visualization and composition analysis to quantify continuous granular mixing processes

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ABSTRACT

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, food processing, and pharmaceutical production. However, characterizing the mixing effectiveness of systems or processes in granular applications is difficult due to challenging sampling procedures and measurement techniques. In this study, a two-part measurement technique consisting of optical visualization and composition analysis is developed to provide qualitative and quantitative mixing characteristics of continuous granular mixing processes, respectively. Mixing studies are performed in a laboratory-scale double screw mixer using a binary mixture of 500–6350 μm red oak chips and 300–500 μm glass beads. The effect of screw rotation speed and dimensionless screw pitch on the mixing effectiveness is investigated for $\omega = 20$, 40, and 60 rpm and $p/D = 0.75$, 1.25, and 1.75, respectively. Optical visualization in terms of video capture is captured across the entire mixing region's periphery, providing extensive qualitative observations. Quantitative composition analysis is performed on samples collected across the screw mixer and a two-way analysis of variance (ANOVA) statistical model is applied. Overall, the mixing effectiveness is maximized at an intermediate screw rotation speed of $\omega = 40$ rpm and a dimensionless screw pitch of $p/D = 1.75$. The developed measurement techniques and resulting trends are compared to previous granular mixing studies featuring similar mixing equipment found in the literature.

1. Introduction

Granular mixing processes can have a significant influence on the resulting products in many industrial processes including energy generation, food processing, and pharmaceutical production. For example, screw pyrolyzers are being developed for the thermochemical conversion of biomass into bio-oil. Screw pyrolyzers are a relatively new chemical reactor design compared to traditional fluidized beds, rotating cones, and ablative reactors. Detailed descriptions of various reactor types used for thermochemical conversion have been previously described in the literature [1–3]. The screw pyrolyzer's high heat transfer rates and resulting bio-oil yields are significantly influenced by its 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, switchgrass, etc.). Previous research efforts featuring screw pyrolyzers have primarily focused on the quality of the products and how they relate to the feedstocks used [4] or the reactor operating conditions [5]. However, no research efforts have focused on relating the granular mixing inside a double screw pyrolyzer to its operating conditions. Thus, a thorough understanding of the granular mixing dynamics is needed for more efficient operation and higher bio-oil yields.

The general purpose of a granular mixing process is that it produces a mixture with an internal structure of acceptable quality [6]. Most commonly, granular mixing processes seek a high degree of homogeneity, and in some particular instances, the purpose is to influence simultaneous processing, such as chemical reactions and heat and/or mass transfer [6]. A fundamental problem commonly encountered during the mixing of granular materials is the tendency for mixtures to segregate due to differences in particle size, shape, and/or density [7]. Further complications arise because a considerably large number of parameters can influence this mixing process.

Despite the solids-handling industry being quite mature, process and equipment design and the selection of operating conditions remains open to speculation because it lacks quantitative justification; it is based primarily on trial-and-error and experience, rather than quantitative science [6]. Moreover, the methods used to determine granular mixing effectiveness are limited [8]. Many experimental studies investigating the mixing of granular materials have considered only a small number of parameters relating to the operating conditions of the mixing equipment. For example, Uchida and Okamoto [9] used an X-ray system coupled with a 2D imaging device to track small amounts of tungsten tracer powder in powder flows and investigated the effect of a single parameter, dimensionless screw pitch, in a single screw feeder.

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In contrast to investigating only one parameter, multiple parameters can and should be studied simultaneously. This allows for a more thorough understanding of the effects the operating conditions have on the mixing effectiveness. Furthermore, it allows for the interaction of parameters to be analyzed. For instance, Vanarase and Muzzio [10] researched the effect of impeller rotation rate, flow rate, and blade configuration in a continuous horizontally orientated impeller powder mixer. The rotation rate was determined to be the most influential parameter and intermediate rotation rates optimized the overall mixing effectiveness. Ideally, numerous parameters that significantly affect the mixing effectiveness of the system would be incorporated in the study, as was done by Vanarase and Muzzio. However, incorporating too many parameters can also be problematic because of the resulting size of the design of experiments, time required to collect and analyze the data, and the ability to interpret the results.

Accurate sampling techniques have been a common problem for many researchers wanting to characterize granular flows. For example, Brown [11] attempted to perform preliminary cold-flow mixing studies by removing the top plate from a screw pyrolyzer designed specifically for chemically reacting flows. The inability to collect samples at locations other than the top layer of material was noted, resulting in the sample composition not accurately reflecting the composition of the entire mixture due to material segregation. Additionally, variations in the material volumetric fill level inside the system resulting from particular operating conditions prohibited collecting samples at all the desired locations. An improved sampling procedure is needed to provide a solution to this commonly encountered problem.

Many attempts to characterize the mixing effectiveness of granular applications rely solely on sampling the material after exiting the mixer and often involve challenging sampling procedures [6, 10–14]. While sampling the granular material after exiting the mixer is very useful, it alone does not provide insight into the mixing dynamics of the mixer during the mixing process. To thoroughly understand the mixing mechanisms, a two-part measurement technique must be developed which couples qualitative observations of the entire mixing process with quantitative data related to the end products.

The purpose of this study is to develop a measurement technique capable of determining the mixing effectiveness of continuous granular mixing processes, and then apply these methods to a laboratory-scale double screw mixer under various operating conditions to demonstrate the usefulness of the developed techniques. The unique screw mixer designed specifically for this mixing study and the granular materials used will first be described. The developed measurement technique, discussed below in great detail, overcomes the previously noted problems by: (i) optical visualization through video capture of the entire mixing region, thus providing a complete picture of the mixing process and qualitative assessment; (ii) utilizing recent advances in rapid prototyping machining processes to enable a more thorough sampling procedure; and (iii) applying a two-way analysis of variance (ANOVA) statistical model to quantitatively indicate the most influential parameters, determine the mixing effectiveness, and optimize the mixing effectiveness for the parameters under consideration. The effect of screw rotation speed and dimensionless screw pitch on mixing effectiveness are investigated and the results of the study are presented, and feature both qualitative observations and quantitative justification. Finally, the experimental procedures are validated by comparing the results of this study to previous mixing studies found in the literature that feature similar mixer geometry.

2. Experimental setup

A laboratory-scale double screw mixer was designed and constructed specifically for granular mixing studies, as shown in Fig. 1. A rapid prototyping machining process (i.e., 3D printer) was used to fabricate all of the screw mixer's parts. The screw mixer housing was manufactured using a transparent plastic material allowing optical access to the mixing region's periphery (360°). All remaining components were fabricated using an opaque plastic material.

The screw mixer features two parallel and horizontally mounted intermeshing noncontact left hand threaded screws. The screw diameter, $D = 2.54$ cm, was chosen as the characteristic length of the system. A variable speed gearmotor drives the screws through a set of specifically designed spur gears. A co-rotating screw rotation orientation was maintained for all mixing studies. Two material injection ports are axially positioned two characteristic lengths apart from one another and are laterally positioned halfway between the two screws. Four uniquely designed outlet ports in the bottom of the screw mixer's housing spatially divide the entire granular flow exit stream into four separate channels. The granular material exits through the outlet ports in the bottom of the screw mixer and free-fall to individual collection basins. The effective mixing length is measured from the centerline of the downstream injection port (port two) to the beginning of the outlet ports thus providing a dimensionless mixing length of $L/D = 10$.

Qualitative optical visualization of the dynamic granular mixing inside the screw mixer was captured from four independent projections simultaneously (i.e., left, top, right, and bottom). Fig. 2 illustrates the experimental setup used to perform the optical visualization, and demonstrates the positioning of four Panasonic HC-V700M HD video cameras, two volumetric auger feeders used to independently meter in the granular materials, the polyethylene inlet and outlet tubes, and the screw mixer. The video cameras capture images at 60 frames per second with 1920 × 1080 resolution. Six 85 W compact fluorescent lamps (CFL) are used to provide adequate lighting to the mixing region. Direct lighting on the outside surfaces of the screw mixer's housing produced significant reflection and other undesired lighting conditions. To minimize these effects, the lights were carefully positioned to provide only indirect lighting and the entire experimental setup was surrounded in black fleece fabric to block any outside light sources. Furthermore, all metallic equipment surfaces (e.g., volumetric auger feeders) were covered in black fabric to eliminate any reflecting surfaces.

The screw mixer mechanically mixes a binary mixture of red oak chips and glass beads. Fig. 3 shows images of the two granular material types that were taken with an Olympus Infinity microscope using a 4× magnification lens. The red oak chips had a particle size range and true density (measured with a pycnometer) of 500–6350 μm and 1350 kg m^{-3}, respectively. The glass beads had a particle size range and true density of 300–500 μm and 2510 kg m^{-3}, respectively. Glass beads were chosen to model traditional heat carrier media used in the biomass thermochemical conversion industry such as refractory sand because the glass beads are well characterized and less abrasive. Furthermore, the glass beads and refractory sand feature similar material properties because the composition of the two materials is very similar. The red oak chips and glass

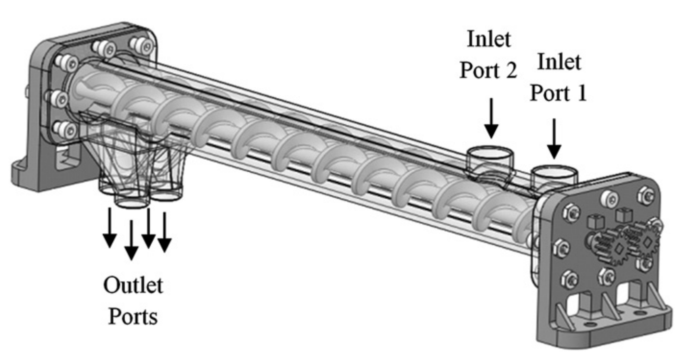

Fig. 1. Screw mixer designed and constructed for optical visualization and composition analysis mixing studies.