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Quantifying mixing in 3D binary particulate systems

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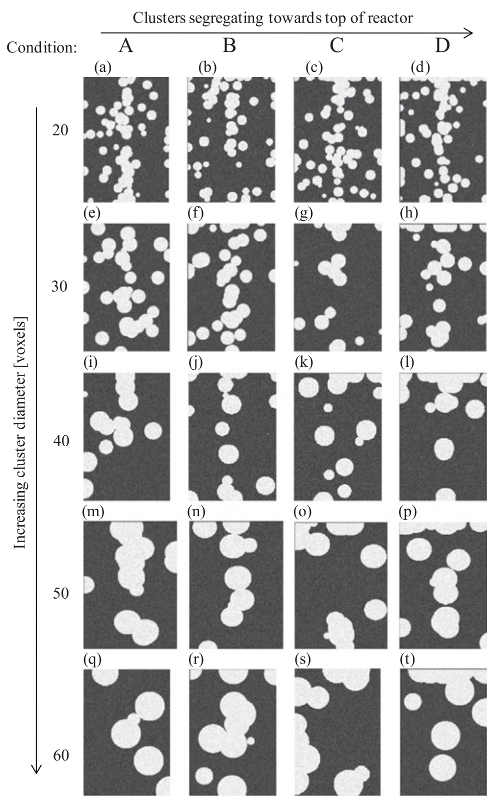
HIGHLIGHTS

- Quantifying mixing/segregation in 3D multi-component particulate systems.
- Two analysis tools are introduced that are superior to existing methods.
- Analysis tools allow quantification of mixedness in 3D particulate systems.
- Sensitivity and completeness of information exceeds earlier introduced methods.
- The findings can help bridge the gap between experimental and computational efforts.

GRAPHICAL ABSTRACT

Sample series of images showing center slice through 3D images with 25% by volume flotsam, and radial location of $r/R = 0.75$.



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ABSTRACT

To evaluate the quality of mixedness in particulate systems, either through experiments or with CFD simulations, proper quantification methods are necessary. Two analysis tools are presented here that allow for quantitative assessment of the mixedness of binary particulate systems when its internal structure is known, either through experimental tomographic techniques or through numerical simulations; they are a newly-defined Particle Segregation Number (PSN) and the Cube

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Analysis (CA). The study has been conducted using simulated material distributions in a 3D cylindrical vessel which approximates a collapsed fluidized bed. The particle distribution is denoted in terms of volume concentration per voxel (i.e., a 3D pixel). The results show that the PSN and CA measures are independent of particle size, material densities, and overall volume fraction, which is not true for other available segregation measures, and can therefore be used over a wide range of operating conditions to assess and compare particulate mixing. Furthermore, it was found that using these methods allows for capturing even small changes in the overall bed segregation condition.

1. Introduction

Mixing of particulate systems is extremely important for many industrial applications such as drying, coating, and gasification in a fluidized bed. For example, when coal or biomass is injected into a bubbling fluidized bed for gasification, the effective mixing of the injected material with the inert heat carrier material is important for efficient gasification (Shen et al., 2007; Zhang et al., 2008). This has led to several investigations in which particle size and/or density were considered in the mixing and segregation behavior of binary fluidized beds. A review of the early work was provided by Rowe and Nienow (1976). They also introduced the terms "jetsam" and "flotsam." Jetsam refers to particles that have a higher density and tend to accumulate on the bottom of the bed, whereas flotsam denotes lower density particles that typically float on the top of the bed. These terms have been expanded to imply that flotsam is always found on the top of the bed and jetsam is found on the bottom, and are not necessarily tied to material density.

García-Ochoa et al. (1989) studied mixing and segregation, varying superficial gas velocities and the mixture composition of binary beds using relatively large particles (in the millimeter range) of differing density. They measured vertical concentration profiles in a circular fluidized bed and compared their findings with a segregation model introduced by Gibilaro and Rowe (1974). To allow for comparison of the experimental results with the model, they needed to be able to express solids concentration as a function of bed height. For this, they used a setup in which vertical plates were inserted into the bed right before the fluidizing gas was shut off, capturing the solids in vertical slices. This allowed for an estimate of the void fractions which was necessary for the model calculations. They found that their experimental technique was reliable and gave reproducible results. The model was also found to satisfactorily predict the average concentrations.

Rice and Brainovich (1986) studied the effects of size differences for equal density particles in binary mixtures. In their study they used both a 2D and a 3D fluidized bed. The 2D fluidized bed was examined by means of visual observations. For the 3D bed, a vacuum was used to remove a small layer from the top after the bed was collapsed by shutting off the fluidizing gas. The extracted particles were then examined through sieving and weighing to find the fractions of the respective particle sizes. To express the "mixedness" of the bed, they used a "mixing index" first introduced by Rowe et al. (1972).

A similar study was completed by Goldschmidt et al. (2003). A 2D bed was utilized with equal density glass beads marked by distinct colors for two different particle diameters that were mixed together in the bed. The fluidized bed vessel was transparent and thus allowed for visual observation of mixing and segregation of the two, distinctly marked, types of particles. The main advantage of this study compared to earlier ones was that modern high speed imaging technology for data acquisition and computer-automated image processing were used. In the scope of this study, a new measure to quantify segregation was also introduced, defined as the "segregation rate".

Others have also investigated mixing and/or segregation in binary systems with applications to fluidized beds (Formisani et al., 2010; Huilin et al., 2003, 2007; Olivieri et al., 2004; Sahoo and Roy, 2008; van Sint Annaland et al., 2009; Wirsum et al., 2001). In all cases, assessing the level of mixedness is important. Two existing measures to quantify mixing of particles in a fluidized bed, as mentioned above, are the mixing index (MI) (Rowe et al., 1972) and the segregation rate (SR) (Goldschmidt et al., 2003).

The mixing index is calculated on the basis of mass fraction of jetsam particles, i.e., those particles that, in general, should be found in the bottom of the bed. It compares the mass fraction of jetsam particles found in the upper region of the bed (x_U), a region which is user defined, with the overall mass fraction of jetsam particles in the whole bed (x_T). It assumes that the jetsam particles are evenly distributed in the upper region. Hence, the mixing index is calculated as (Rowe et al., 1972)

$$\mathrm{MI} = \frac{x_U}{x_T} \times 100\% \tag{1}$$

For MI=0, the bed is completely segregated about a horizontal plane and for MI=100% the bed is perfectly mixed. The restrictions for the mixing index are illustrated in Fig. 1, namely the assumption of an even distribution of jetsam in the upper region of the bed, as illustrated in Fig. 1b.

The segregation rate uses the average heights above the distributor, as well as the mass fraction of flotsam and jetsam particles. For Goldschmidt et al. (2003), small particles congregated on the top of the bed and are referred to as flotsam while large particles are found in the bottom of the bed and are jetsam. The segregation rate is defined as (Goldschmidt et al., 2003)

$$\mathrm{SR} = \frac{S-1}{S_{max}-1} \times 100\% \tag{2}$$

where S is the ratio of average heights of small (flotsam) to large (jetsam) particles, calculated as

$$S = \frac{h_{small}}{h_{large}} \tag{3}$$

where h_{small} is the average height above the distributor of small particles, and h_{large} is the average height above the distributor of large particles. S_{max} contains the maximum degree of segregation and is calculated in terms of the mixture composition as

$$S_{max} = \frac{2-x_{small}}{1-x_{small}} \tag{4}$$

where x_{small} is the mass fraction of small particles. When SR=0, the bed is perfectly mixed, and when SR=100%, the bed iscompletely segregated.