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Kinetic theory-based numerical modeling and analysis of bi-disperse segregated mixture fluidized bed

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ABSTRACT

We discuss a series of continuum Euler-Euler simulations of an initially mixed bi-disperse fluidized bed which segregates under certain operating conditions. The simulations use the multi-phase kinetic theory-based description of the momentum and energy exchanges between the phases by Simonin's Group [see e.g. Gourdel, Simonin and Brunier (1999). Proceedings of 6th International Conference on Circulating Fluidized Beds, Germany, pp. 205–210]. The discussion and analysis of the results focus on the fluid-particle momentum exchange (i.e. drag). Simulations using mono- and poly-disperse fluid-particle drag correlations are analyzed for the Geldart D-type size bi-disperse gas-solid experiments performed by Goldschmidt et al. [Powder Tech., pp. 135–159 (2003)]. The poly-disperse gas-particle drag correlations account for the local particle size distribution by using an effective mixture diameter when calculating the Reynolds number and then correcting the resulting force coefficient. Simulation results show very good predictions of the segregation index for bi-disperse beds with the mono-disperse drag correlations contrary to the poly-disperse drag correlations for which the segregation rate is systematically under-predicted. The statistical analysis of the results shows a clear separation in the distribution of the gas-particle mean relaxation times of the small and large particles with simulations using the mono-disperse drag. In contrast, the poly-disperse drag simulations have a significant overlap and also a smaller difference in the mean particle relaxation times. This results in the small and large particles in the bed to respond to the gas similarly without enough relative time lag. The results suggest that the difference in the particle response time induce flow dynamics favorable to a force imbalance which results in the segregation.

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1. Introduction

Density and/or particle size segregation is a phenomenon which can occur in gas–solid fluidized bed systems. There are numerous technological processes using fluidized beds for which better understanding, prediction and/or control of this phenomenon would be advantageous. For instance, the operation of the Chemical-Looping Reactor with the solid fuel such as the coal particles produces ash as the combustion wastes which must be removed from the fuel reactor to avoid reducing the lifetime of the oxygen carrier particles (Lyngfelt & Leckner, [21]) and maintain the efficiency of the system. For such a process the segregation between the species of the particle mixture is considered as a plausible stage of the process.

Following Gera et al. [13], the segregation of a binary initially well-mixed size mixture is likely to occur only when the fluidization velocity is in between the minimum fluidization velocities of the smaller and the larger particles. Wu & Baeyens [44] correlated the size mixing/segregation index of binary mixtures to the visible bubble flow rate (or excess gas velocity) and the particle size ratio. Formisani et al. [10,11]) showed that the minimum fluidization velocity of the mixture cannot be the threshold velocity between mixed and segregated bed states. Instead these authors propose a velocity interval to bound the segregated bed regimes with an extent dependent on both the mixture composition and initial segregation state. Marzocchella et al. [23] and Olivieri et al. [28] also identified the existence of such a velocity range whose bounds are dependent on the initial bed composition. For instance, they reported that the broadest width of this velocity range associated with the bed material of their binary mixture experiments occurred with mixtures of about 80% of jetsam (i.e. the particles migrating downwards). Furthermore, these authors found that the lower bound of the velocity interval can be smaller than the minimum fluidization velocity of the flotsam (i.e. the particles migrating upwards), while the upper bound lies in between the minimum fluidization velocities of the flotsam

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and of the jetsam. Marzocchella et al. [23] and Olivieri et al. [28] also found that the segregation dynamics is closely related to this velocity interval. Thus, closer the gas superficial velocity is to the upper bound velocity and relatively faster is the segregation rate.

Fig. 1 sketches the fluidization regimes of binary mixture beds following Formisani et al. and Gera et al.

Specific mechanisms controlling the segregation are still not completely understood. With a simple force balance, Di Maio et al. [7] proposed a simple model for the initial segregation pattern at incipient fluidization for an initially well-mixed binary mixture. However, the extent of the segregation is not explicitly predictable using this model. From a detailed modeling perspective, the tendency of particle phases to separate or mix in fluidized bed is mainly attributable to the interaction of the momentum exchange between: (*i*) the fluid and the particles, i.e. the fluid-particle drag force acting on the particles and (*ii*) the poly-disperse particles of the mixture due to the inter-particle collisions.

For a Lagrangian approach the particle collisions are explicitly calculated or resolved and therefore the modeling error in the prediction of the momentum exchange due the inter-particle collisions is reduced. However, there is still the question of how to include the effects of poly-dispersity into the fluid-particle drag closure. The DEM simulations presented by Beetstra et al. [1] suggest that a drag model which explicitly incorporates poly-dispersity effects may be required to improve predictions of the segregation dynamics of size binary mixture.

Similarly, to account for the influence of the neighboring particles on the drag force and better capture the segregation dynamics in DEM simulations, Dahl & Hrenya [6] applied a correction factor to a mono-disperse drag model in the dilute regions of the bed. This correction factor was dependent on the local volume fraction and local average diameter of the solid phases.

In contrast to the studies above, Norouzi et al. [26] do not use a poly-disperse fluid-particle drag model. Instead the authors combined the mono-disperse drag models of Ergun [12] and Wen & Yu [43]. The DEM simulations of the binary mixture experiments of Goldschmidt et al. [15] successfully compare with measurements of the extent of segregation and the mean bed height.

For the Eulerian modeling approach, in addition to the fluid-particle momentum closures, closures are also required for the momentum exchanges between the different particle phases. Kinetic theory provides a systematic approach to derive models for the dynamics of the continuum particle phases from particle scale collision dynamics. Using a particle-particle model derived from a multi-fluid kinetic theory model based on a Chapman-Enskog expansion method, van Sint Annaland et al. [40] & [41] simulated the dynamics of size binary mixture fluidized beds. The authors concluded that the simulations achieved moderate agreement with the measurements and attributed the absence of friction in the model as a primary cause of any deviations between the simulations and measurements. Mazzei et al. [25] examined the segregation dynamics of the binary mixture experiments of Marzocchella et al. [23], by supplementing Schaeffer's [33] plastic stress due to the particle long lasting contacts to a multi-fluid model. The stationary axial segregation of the bed was reasonably well predicted for superficial velocity in between the velocity bounds where the segregation is likely to occur. However, the model fails to predict the upper limit of the segregation velocity interval.

In earlier modeling study of binary-sized mixture, Gera et al. [13] combined the kinetic theory-based sliding friction particle-particle drag from Syamlal [37] with an additional model for a "hinderance effect". This second model accounts for the tendency of the different particle phases to move as a single phase as the packing limit is approached. Successful predictions of the segregation extent of binary mixtures were reported using that model (see e.g. Gera et al., [13]; Fan & Fox, [8]). However, the model contains a coefficient which must be calibrated for a given mixture of particles.

Arguing that the friction between the particles dominates over momentum exchange due to binary collisions, Chao et al. [4] introduce a model similar to Syamlal [37] to account for the effects of longer lasting contacts by mean of a correction friction coefficient. After calibrating this correction friction coefficient, the model predictions of the segregation extent for the binary beds successfully compare against measurements.

This effort discusses the validation and associated modeling issues for the binary fluidized bed experiments conducted by

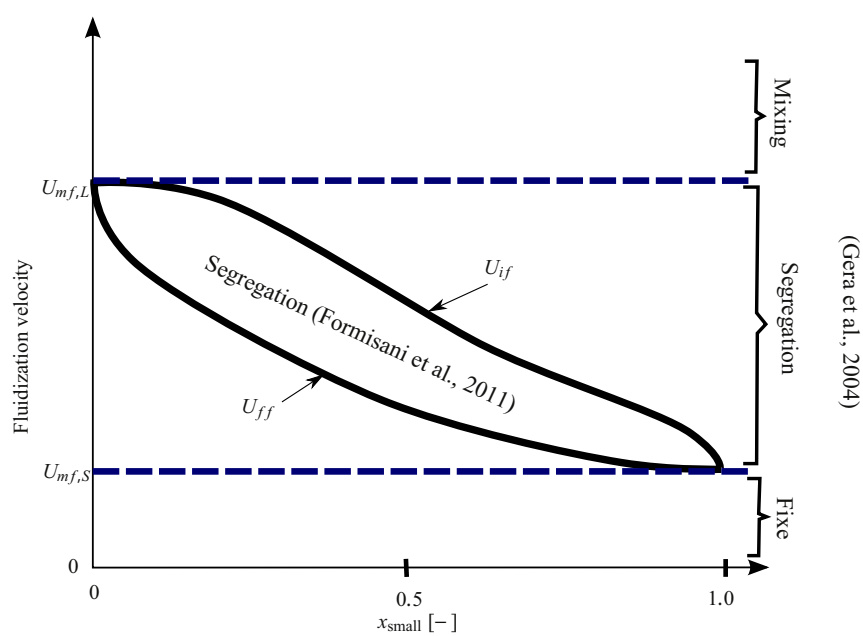

Fig. 1. Diagram of the fluidization patterns of binary mixture system. Formisani et al. [11] shows a density-based binary mixture: U_{if} is the initial fluidization and U_{ff} refers to the velocity at which fluidization state is achieved. $U_{mf,S}$ and $U_{mf,L}$ denote the minimum fluidization velocities of the small and large particles, respectively.

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