Mixing in a Size Segregated Fluidized Bed: Simulations and Experiments

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1 Introduction

Fluidization is commonly used in process, food and pharmaceutical industries [1]. Majority of the literature on fluidization is focused on monodispersed beds though the actual fluidized beds have wide particle size distribution [2]. Also, fluidization behaviour of the bed changes with bed particle diameter [3]. It has been well established in the literature that existing relations to predict characteristic velocity for a mono component bed should not be used for a polydisperse bed. A fluidized bed study aiming to understand practical applications must account for polydispersity [2]. Experiments with bi-disperse beds are reported in the literature. Change in constituent particles' mass fraction leads to change in bubbling behaviour which is ultimately related to mixing behaviour [1]. Similarly, simulations were performed to understand mixing/segregation in a fluidized bed. Simulations were performed using either TFM or DEM schemes. Details of the same are given in the next section.

2 Literature Review and Objective

Mixing and segregation are two main features of the fluidization process. Sincere efforts have been made by the researchers to understand mixing–segregation occurring in a fluidized bed. A very basic classification of the particles was proposed by Geldart [3]. Numerous experiments as well as simulations are reported in the literature to understand the mechanism of mixing/segregation. Formisani et al. [2, 4, 5] have reported several articles to understand characteristic velocities of a fluidized

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bed. The authors came to a conclusion that minimum fluidization velocity (u_{mf}) is best suitable for a mono component bed only. For a binary bed, initial fluidization (u_{if}) and final fluidization (u_{ff}) velocities should be used as characteristic velocities [2]. Gilbertson and Eames [6] reported vertical segregation of particles in an initially mixed bed. People have reported experiments with biomass particles as well to understand fluidization behaviour. Such a study was reported by Abdullah et al. [7]. Size segregating as well as density segregating mixtures were investigated and compared by Joseph et al. [8] with glass and polystyrene particles. Non-intrusive methods have been employed to understand fluidization mechanisms. Upadhyay and Roy [9] reported a study with binary particles using radioactive particle tracking and dual source densitometry. Polydisperse particles in a CFB riser were reported by Chew et al. [10] with size segregating and density segregating mixture. Rao et al. [11] used a size and density segregating bed to understand segregation in a fluidized bed. In this study, the bed was divided into multiple sections and later components were segregated to understand particle mixing. The authors mentioned that fluidization behaviour is affected by initial bed arrangement.

A size segregating mixture was reported by Huilin et al. [12]. The authors reported a model based on fluid particle drag. With the help of simulations, fluctuating kinetic energy of the particles was predicted. Feng et al. [13] used DEM to understand mixing in a fluidized bed. Simulations were performed for a size segregating binary mixture, where particles belonged to Geldart 'D' classification. Bubbling behaviour which is responsible for mixing/segregation was discussed in detail. Cooper and Coronella [14] reported simulations for density as well as size segregating mixture. The results concluded that mixing in case of a density segregating mixture was poor as compared to a size segregating mixture. Sun and Battaglia [15] performed simulations for a mono as well as a binary bed using MFIX software. The main aim was to study the effect of inclusion of particle rotation. It was concluded that inclusion of particle rotation resulted in realistic results. Di Maio and Di Renzo [16] presented simulations using DEM for a pseudo-3D bed to understand mixing. The results were compared with experimental data. Sun et al. [17] proposed a model to understand mixing. The model was used for particles of varying size but of same density. The new model was said to have outperformed multi-fluid model. One can conclude from the literature review that the initial bed configuration influences the fluidization behaviour. The objective of the present work is to investigate the fluidization and the de-fluidization behaviour of an initially segregated bed using laboratory scale experiments and numerical simulations.

3 Methods

3.1 Experiments

Figure 1 shows the experimental set-up. The experiments were performed in a transparent glass column of 50 mm inner diameter. Compressed air from the compressor reaches to the bed after passing first through a diffuser and later a distributor plate. The supplied air was ensured to be completely moisture free before reaching the set-up. Pre-calibrated rotameters were used to control the air flow. Pressure drop across the bed was measured using a manometer. Pressure drop due to the distributor plate at each air velocity was deducted from the total pressure drop values to get actual bed pressure drop. Glass particles belonging to Geldart 'B' group having diameter ratio (jetsam to flotsam) as 2.8 were investigated.

It was made sure that the particles used for the experiments are completely moisture free by keeping particles into oven prior to starting each experiment. The bed condition at each velocity point was captured with the help of a Nikon DSLR camera with the highest possible resolution. Actual bed height was noted with the help of

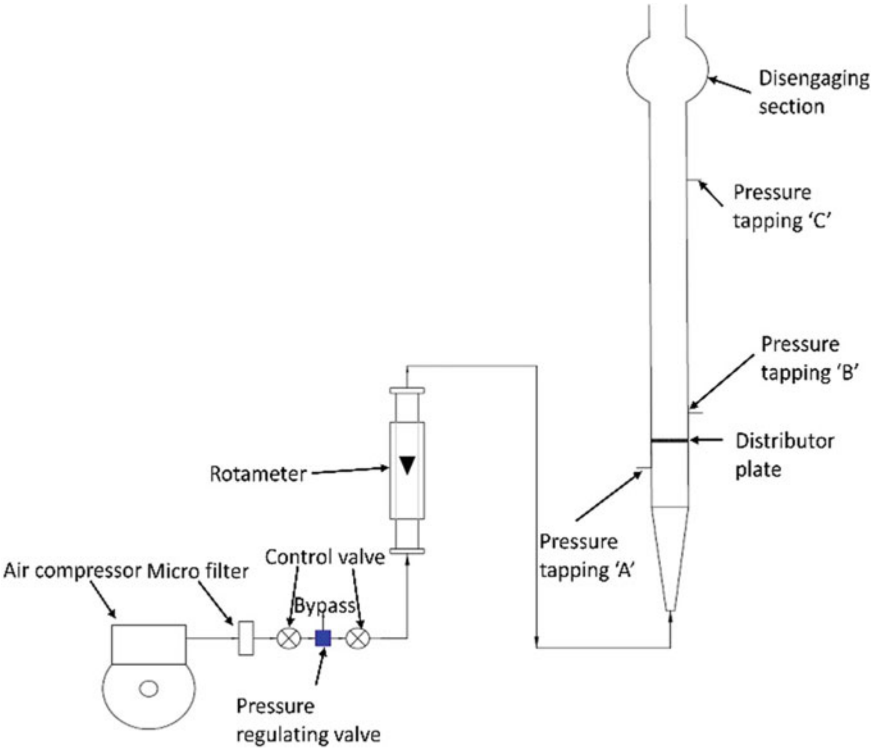

Fig. 1 Schematic diagram of the set-up

a scale attached to the set-up. The experiments were performed for both increasing as well as decreasing cycle of gas velocity. Each time, it was made sure that the bed pressure drop is stable prior to moving to next velocity point.

In current experiments, jetsam particles were put at the bottom of the bed. The flotsam particles were poured on top of the jetsam particles. Gas velocity was slowly increased. Once the bed looked fully fluidized, the bed was brought back to still condition. Initial and final state of the bed remains the same as flotsam on top of the jetsam. Also, x_{FO} is based on a fraction of the flotsam particles in the bed.

3.2 Simulations

Multiphase Flow with Interphase exchanges (MFIX) which is an open-source code was used for running the two-fluid model (TFM) simulations. TFM is based on the Eulerian-Eulerian approach and treats both the dispersed and fluid phases as interpenetrating continua. It requires less computational time and effort than Lagrangian methods. In this work, numerical simulation of a binary granular system with particles of different sizes but same density was performed to analyse the behaviour of the interacting particles. The stacking order, namely LBST (i.e. large bottom small top) was taken as the initial bed condition. The Syamlal-O'Brien drag correlation was used to model the interaction force between different phases [18]. The model geometry and parameters are summarized in Table1.

The friction stress model of Schaeffer [19] with a minimum solid volume fraction value of 0.5 was included. Instead of the viscous stress model of Lun et al. [20], the default algebraic formulation was selected which uses an algebraic granular energy equation.

Table 1 Simulation parameters

Cell size (m)	0.0025
Coefficient of restitution (e_n)	0.95
Friction coefficient (μ)	0.1
Drag correlation	Syamlal—O'Brien
Time step (s)	10^{-4}
Superficial gas velocity (m/s)	0.13 and 0.17
Particle material	Glass
Particle size (m)	196×10^{-6}, 550×10^{-6}
Particle shape	Spherical
Particle density (ρ_p)(kg/m^3)	2500
Fluid density (ρ_f)(kg/m^3)	1.25
Packed bed void fraction	0.38
Initial bed height (m)	0.096

A uniform grid of size 2.5 mm (nearly 4 times large particle diameters) was used. The selected cell size was large enough to predict the local void fraction and fine enough to precisely solve the governing equations. The bed was simulated for 20 s for a particular gas velocity. Chosen time step was 10^{-4} s. A mass flow boundary condition was specified at the inlet and pressure outlet boundary condition at the top.

4 Results and Discussion

Figure 2 shows variation of absolute pressure drop and height with variation in superficial gas velocity for an initially segregated bed with flotsam on top of jetsam with $x_{FO} = 0.5$. The figure shows the initial and final states of the bed. Initially the segregated bed is in a packed state. As the gas velocity is increased, bubbles appear in flotsam layer. With further increase in gas velocity, bubbling intensified.

Figure 3 shows a snapshot of the fluidized bed at $u_g = 17$ cm/s. At the bottom of the bed, the jetsam particles are seen. Above the jetsam particles, there are flotsam particles. On top of the bed, an eruption of bubbles can be seen with a small fraction of particles. Also a bubble can be seen above the interface of the jetsam and the flotsam particles. At a certain velocity, the jetsam layer started to expand. With a further increase in the gas velocity, mixing in the interface between the jetsam and the flotsam layers is observed. The mixed layer started growing with further increase in the gas velocity. The jetsam layer thickness reaches a minima after which the layer thickness starts increasing. Formisani and co-workers [2] defined final fluidization velocity (u_{ff}) based on pressure drop curve only. In this case, the initiation of fluidization in the

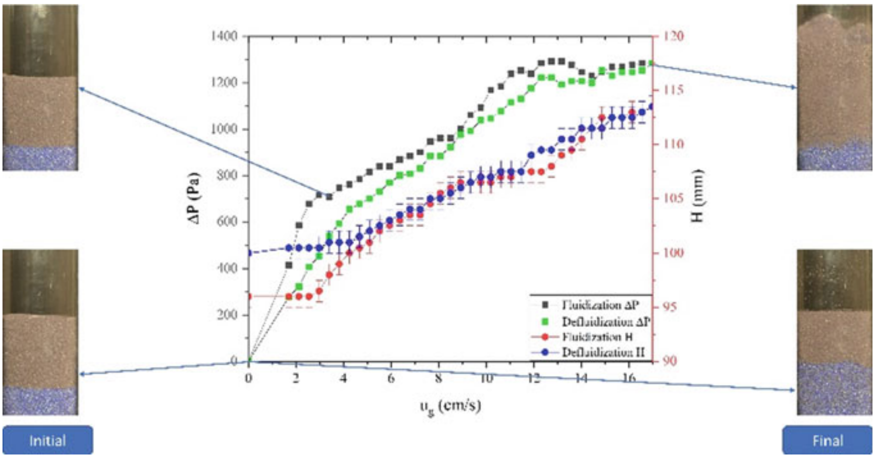

Fig. 2 Absolute pressure drop and height variation with superficial gas velocity for increasing and decreasing cycle for an initially segregated bed with flotsam particles on top of the jetsam with $x_{FO} = 0.5$

Fig. 3 Snapshot of bed at 17 cm/s

bed is characterized by the minimum fluidization condition of the flotsam particles. There is an intermediate fluidization point, at which the jetsam layer begins to expand before the bed is completely fluidized. Earlier literature [2] has suggested only two velocities, namely the initial and final fluidization velocity deciphered from the bed pressure drop; however, a careful experiment shows existence of three characteristic velocities.

Next, the simulation results are compared against the experimental observation. As a first check of the simulations, the pressure drop obtained from numerical simulations were compared against the experimentally measured values. The pressure drop values predicted by experiment and simulations for two different gas velocities are compared in Fig. 4. The difference between results is found to be ~ 4%.

Figure 5 shows the volume fraction of the flotsam particles at different time values for $u_g = 13.175$ cm/s. Figure shows variation in volume fraction of flotsam particles at different time instances. As the inlet $u_g = 13.175$ cm/s is well above the minimum fluidization velocity (u_{mf}) of the flotsam particles, multiple bubbles are apparent in the flotsam layer of the bed at $t = 3.1$ s. It is also clearly seen that the flotsam particles layer expands uniformly towards the bottom of the bed. Correspondingly, change in the volume fraction can be seen.

Figure 6 shows the volume fraction of the flotsam particles at different time values for $u_g = 17$ cm/s. As compared to Fig. 5, larger and more bubbles are seen at $u_g =$ 17 cm/s. Variation in volume fraction behaviour for both the cases seems similar. As seen in the figure, presence of gas bubbles in upper most layers is comparable to that seen in Fig. 3.

The results show good overall agreement between the simulations and the experiments.

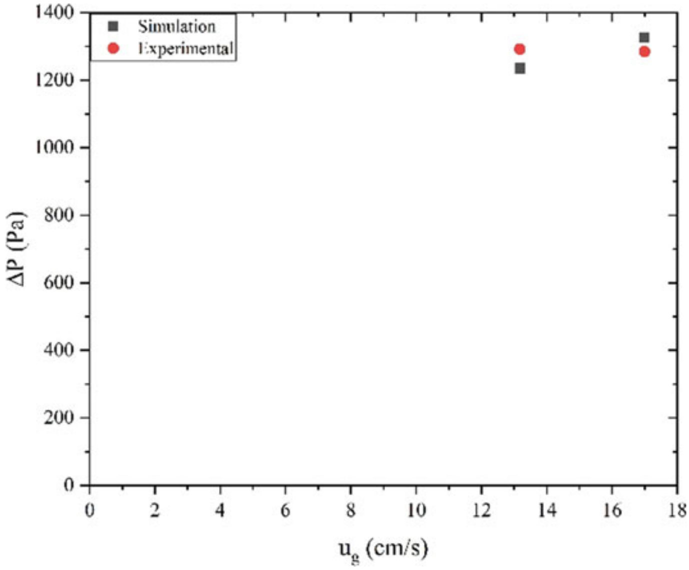

Fig. 4 Comparison between pressure drop predicted by simulations and experiment at two different gas velocities

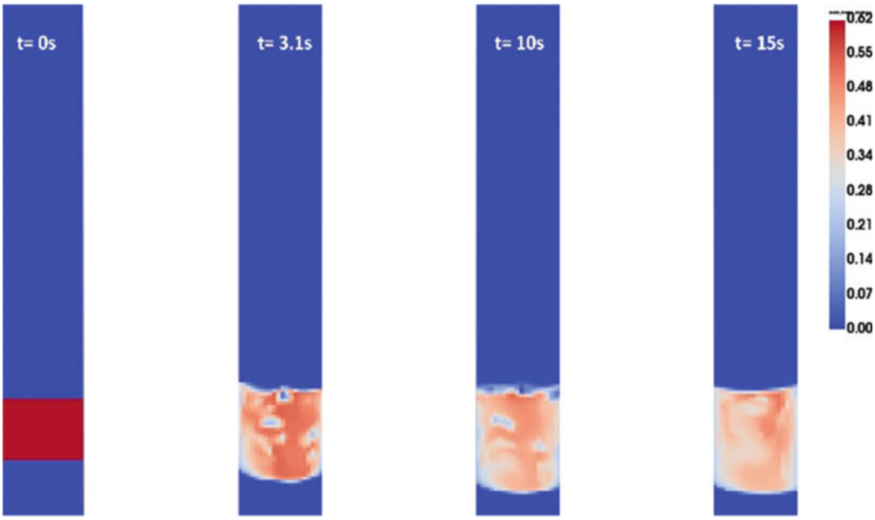

Fig. 5 Snapshots of the volume fraction predicted by TFM simulations of flotsam at $t = 0$ s, $t = 3.1$ s, $t = 10$ s and $t = 15$ s at $u_g = 13.175$ cm/s for $x_{FO} = 0.5$

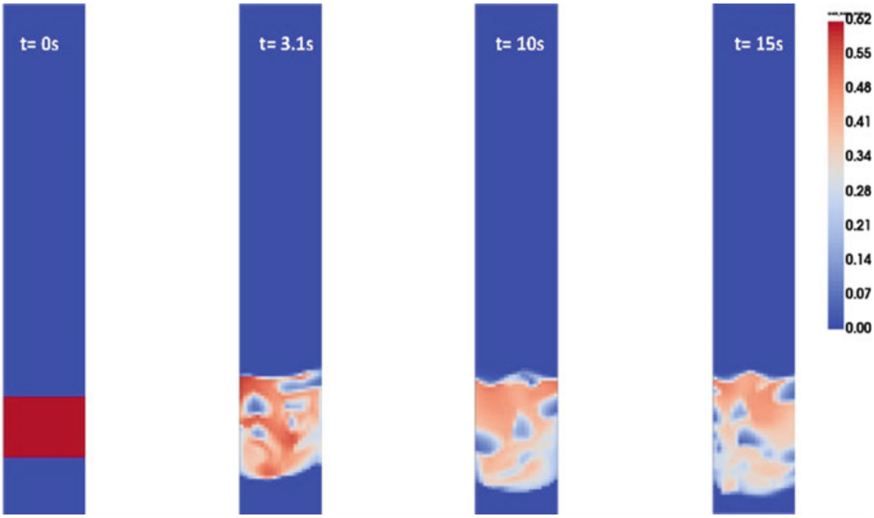

Fig. 6 Snapshots of the volume fraction predicted by TFM simulations of flotsam at $t = 0$ s, $t = 3.1$ s, $t = 10$ s and $t = 15$ s at $u_g = 17$ cm/s for $x_{FO} = 0.5$

5 Conclusions

Experiments were performed for a fluidized bed consisting of particles of the same material but with different sizes. The inlet gas velocity was initially increased till the bed looked fully fluidized. Later, it was decreased to bring the bed back into a packed state. At the end of defluidization, the bed was the same as in initial condition, a segregated bed with the flotsam particles on top of the jetsam particles. Through the experimental run, the bed condition was monitored. Variation in the jetsam layer height was observed with change in gas velocity. The jetsam particle layer shows increasing trend initially with increase in gas velocity. Minima of the jetsam layer height was found near final fluidization velocity (u_{ff}). Simulations with two fluid models were performed using MFIX software with appropriate drag models. Simulations are performed for a particular mixture composition and two different gas velocities. Pressure drops obtained from simulations are in good agreement with the experimental observations. It is also noticed that the jetsam layer thickness shows a qualitatively similar behaviour as observed in experiments.

Nomenclature

e_n Coefficient of restitution
ρ_f Density of fluid (kg/m^3)
ρ_P Density of particle (kg/m^3)

M Friction coefficient
u_{ff} Final fluidization velocity (m/s)
u_g Gas velocity (m/s)
u_{if} Initial fluidization velocity (m/s)
u_{mf} Minimum fluidization velocity (m/s)
x_{FO} Mass fraction

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