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Two Dimensional Computational Fluid Dynamics Studies of a Fluidized Bed with Binary Solid Mixtures

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Abstract. In the present work, hydrodynamics of a fluidized bed with binary solid mixture have been studied using CFD simulations. Two different cases one with binary mixtures of 20% large and 80% small particles and other with 40% large particles 60% small particles respectively (both of Geldart B type) are chosen. Transient and steady state flow patterns have been reported for understanding the stability and increase in bed height for the chosen mixtures. Further, the velocity, turbulence parameters and solid volume fraction profiles have been analyzed to understand the characteristics like mixing and segregation in the beds

Keywords. CFD, fluidized bed, binary mixtures, flow patterns, bed segregation.

1. Introduction

Gas-Solid fluidized beds have wide applications as reactors, dryers, blenders, and various other applications. Particle size distribution plays a significant role in fluidization with other parameters specifically geometric parameters like bed height, height to diameter ratio and operating parameters like superficial velocity. Hydrodynamics and transport phenomena in fluidized beds with binary mixtures are different than those with uniformly sized particles. This has been evident from several experimental studies using pressure fluctuations and recently with CFD studies. The binary mixture behavior varies from segregation to mixing particles in a fluidized bed. Segregation of coal particles in syngas production leads to unreacted reactants, which are neither practical nor helpful. Furthermore, segregation and mixing phenomena in fluidized beds with binary mixtures is important for scale-up and can be investigated with CFD modeling with reliable models.

2. Literature Review

CFD Modeling of GS fluidized beds for binary mixtures is more concentrated towards understanding the model parameters (like drag models, turbulence models etc.) which can reliably predict bed dynamics. Experimental investigations for binary mixtures also involve characterization of fluidized beds in terms of mixing and segregation.

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Analyzing the velocity profiles of particles provides us with important insights in the same. Table 1 shows some of the prominent experimental and CFD research works.

Table 1.

Authors	Material and Particle diameter (μm)	Wt. fraction (range)	Fluid density ($kg{\cdot}m^{-3}$)	Fluid viscosity (Pa·s)	Superficial gas velocity range (m/s)	Particle density ($kg{\cdot}m^{-3}$)	*Key objective
Pei et al.[1]	Resin: 670 Rapeseed: 1525	0.1-0.9	1.21	1.81×10^{-5}	*0.2-0.45	Resin: 1448.3 Rapeseed: 1105.5	1
Zaabout et al.[2]	Glass: 107, 175	NA	1.21	1.81×10^{-5}	*0-1.6	Glass: 2400	2
Jayarathna and Halvorsen, [3]	Glass: 154, 488	0-1	1.21	1.81×10^{-5}	0.031-0.307	Glass: 2485	3
Kotoky et al. [4]	350, 400, 450, 500	0.58	1.21	1.81×10^{-5}	0.54	2000	4
Chew and Cocco, [5]	Glass: 170, 650 HDPE: 650 Polystyrene: 327.5 Sand: 196	0.25-0.75 of large glass particles	Air: 1.21	Air: 1.81×10^{-5}	FFR*: 10–17 Turbulent FR*: 1.5 and 1.7	Glass: 2500 HDPE: 900 Polystyrene: 1050 Sand: 2650	5
Sadiq et al. [6]	Soyhull pellet: 5000; cylindrical Oathull pellet: 5500 cylindrical Sawdust: 1120 Silica sand: 329	NA	Air: 1.21	Air: 1.81×10^{-5}	0-0.5	Soyhull pellet: 1543 Oathull pellet: 1342 Sawdust: 1511 Silica sand: 2650	6

*Key objective: 1. To study the effect of superficial gas velocity on the mixing of bed and penetration depth of the jet inside the bed 2. Characterization of particle behavior for a Circulating fluidized Bed Riser in turbulent regime 3. Study of effect of superficial gas velocity and particle size distribution on fluidization of bed, pressure variation with particle size variation 4. To study the effect of particle size distribution on volume fraction, pressure drop and particle velocity. 5. To study the segregation and mass flux estimations based on different predictors for fast fluidization and turbulent regimes 6. Experimental investigation of mixing and segregation of binary mixtures of biomass and sand.

Zaabout et al. [2] experimentally found two axial particle velocities: parabolic and concave for two different size distributions of single particles. The experiments were carried out in a circulating fluidized bed riser for turbulent regimes. The parabolic profiles for observed for large particle sizes. Both the profiles showed increase in the mean axial velocity with increasing superficial gas velocity. Jayarathna and Halvorsen [7] did experimental and numerical studies for fluidized beds with binary mixtures of glass particles. They observed that the fluid tends to escape the solid beds in a zigzag pattern forming bubbles in certain places. Kotoky et al. [4] used the Eulerian-Eulerian fluid flow model and KTGF model in an in-house code for studying the fluidized bed. They concluded that particle diameter has significant importance in fluidized bed characteristics. This study aims to understand the dynamics of the binary mixture fluidized bed.

However, the significance of solid mixing in fluidized beds with binary mixtures by analyzing the axial particle velocity and turbulence profiles along with bed volume fractions have received less attention. In the present work, an effort has been made to understand the dynamics of the bed in two steps (a) qualitative analysis of both transient and time averaged steady state flow patterns (b) studying the different profiles at different axial locations. The geometry of lab scale setup from available literature and their operating conditions would be used for simulations

3. Grid and Methodology

The 2D simulations were carried out in Ansys Fluent 18.1 software. The height and width of the computational bed are 1.4 and 0.072, respectively. Figure 1 (A) shows the schematic diagram of the geometry with an initial bed of solid particles at t=0s. Here, H_s represents the extended bed height. Figure 1 (B) indicates the different axial and radial data collection methods. After doing grid sensitivity, a mesh with 12720 elements is considered. The various models used for the simulation are given in Table 2. The fluid properties used for simulation are provided in Table 3, which were experimentally used by Jayarathna and Halverson [7] . For simulating, weight averaged mean particle diameter is considered as particle diameter. Simulations were carried out for three different mixtures of 20% and 40% large particles with a bed height of 0.235m. Table 4 summarizes the parametric values used for the simulations. The total run time for the simulations is 7 seconds with a time-step size of 0.1 seconds. The initial volume fraction of particles in the bed is taken as 0.58 for the 20% mixture and 0.56 for the 40% mixture.

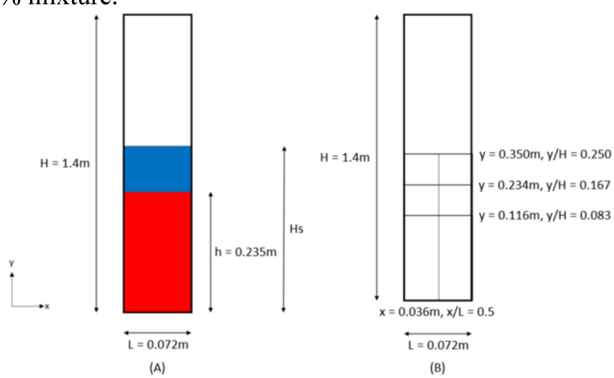

Figure 1. Schematic Diagram of the geometry (A) with an initial bed of solid particles at t=0s (B) Horizontal lines denote different axial locations for radial profiles while vertical centerline denotes centerline for axial profiles Red color denotes solid volume fraction 1 while blue color denotes solid volume fraction of 0.

Table 2. Different Models used for the simulations.

Property	Model Used
Multiphase	Eulerian
Viscous	k-ε (Standard)
Granular Viscosity	Syamlal & O'Brien
Granular Bulk Viscosity	Lun-et-al
Frictional Viscosity	Schaeffer
Frictional Pressure	KTGF
Frictional Modulus	Derived
Granular Temperature	Algebraic
Elasticity Modulus	Derived
Drag	Syamlal & O'Brien

Table 3. Solid and fluid Properties from literature data (Jayaratna and Halvorsen [3]).

Fluid Phase Properties		**Solid Phase Properties**	
Density (kgm^3)	1.22	Density (kgm^3)	2485
		Viscosity ($kgm^{-1}s^{-1}$)	0.00082
Viscosity ($kgm^{-1}s^{-1}$)	0.000017	Small Particle Diameter (μm)	154
		Large Particle Diameter (μm)	488

Table 4. Simulation Details.

% Of Large Particle	**Particle Diameter (μm)**	**Superficial Gas Velocity (m/s)**	**Initial Bed Height (m)**
20%	220.8	0.143, 0.184, 0.225, 0.266, 0.307	0.235
40%	287.6	0.031, 0.032, 0.041, 0.061, 0.102, 0.266	0.235

4. Result and Discussion

4.1. Model Validation

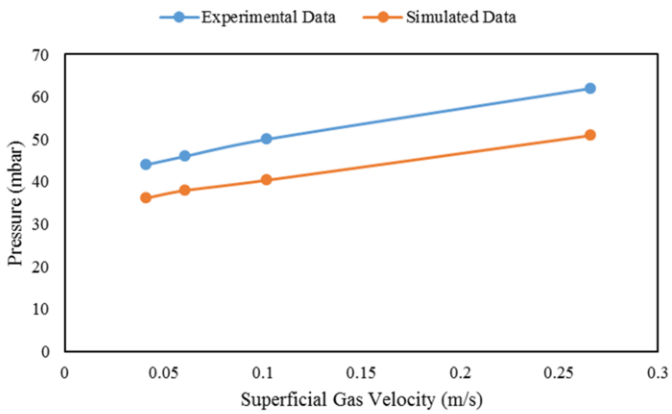

Figure 2. Model Validation for 40% mixture with an initial bed height of 0.235m at different superficial gas velocities with literature data (Jayaratna and Halvorsen [3]).

Figure 2 shows the model predictions with respect to experimental data. for the 40% mixture. Deviation between model predictions and experimental data is around 20%. The reasons for the deviation are due to (i) unavailability of distributor design for the experimental geometry used for simulations and (ii) two dimensional simulations were carried out instead of 3D simulations

4.2. Flow Patterns

Figure 3 (A) shows the transient volume fraction contours for a 40% mixture with 0.266m/s superficial gas velocity and 0.235m initial bed height. The model is able to predict the bed expansion charasteristics for unsteady mode of operation.

Figure 3 (B) shows the time averaged volume fraction contours for the 20% mixture at a steady state time of 7 seconds at different superficial gas velocities. The increase in bed height with increase in superficial velocity complies with available data in published literature.

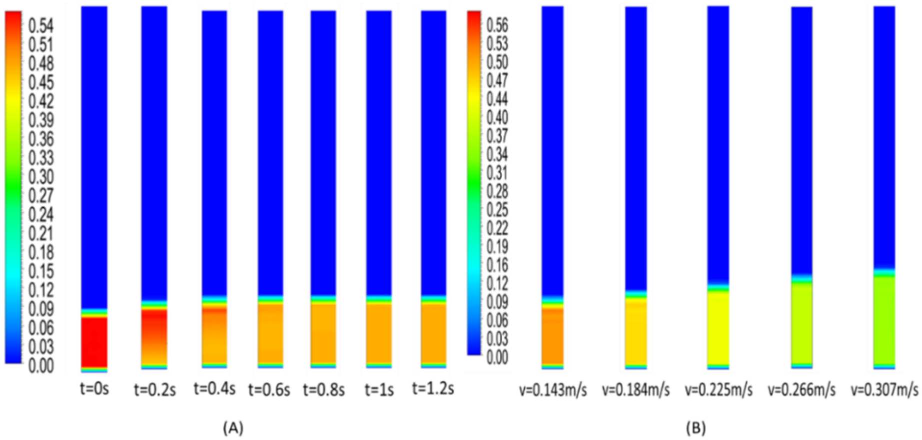

Figure 3. Particle Volume Fraction Contours for (A) Transient simulation for 40% mixture with a superficial gas velocity of 0.266m/s and an initial Bed Height of 0.235m (B) Steady-state simulation for 20% mixture with an initial Bed Height of 0.235m with different superficial velocities.

4.3. Profiles of Velocity, Volume Fraction and Turbulence Quantities

4.3.1. Particle Velocity Profiles

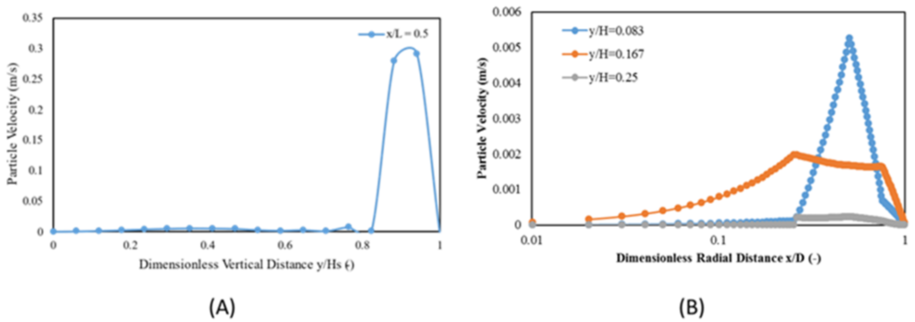

Figure 4. Steady-State Particle Velocity Profiles for 20% mixture, 0.235m initial bed height, and superficial velocity of 0.225m/s (A) Vertical Centerline (B) Horizontal locations.

Figures 4A and B show time averaged axial particle velocity profiles across dimensionless vertical and horizontal distance respectively. Centerline vertical axial profiles show that the particle velocities are high at $0.8 < y/Hs < 1$ which implies the rest of the bed is stagnant to reaffirm our observation we plot radial profiles of particles at different axial locations varying in horizontal direction. An assymetric profile of the gas shifted towards right is observed at the axial positions chosen for understanding the radial particle velocity profiles. Further, the magnitudes decrease from the lower most position to the topmost position. The highest particle velocities in radial profiles are two orders of magnitudes lower than the axial particle velocities.

4.3.2. Turbulent Kinetic Energy Profiles

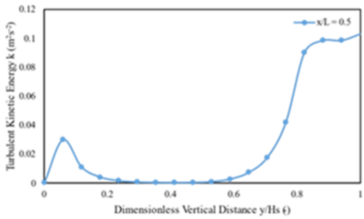

Figure 5. Steady-State Turbulent Kinetic Energy (TKE) Profiles for 20% mixture, 0.235m initial bed height, and superficial velocity of 0.225m/s (A) Centerline (B) Horizontal profiles at different axial locations.

Figure 5 shows the steady-state axial profile for turbulent kinetic energy (TKE) at the centerline for a 20% mixture, 0.235m initial bed height, and superficial velocity of 0.225m/s. The profiles clearly denote that the TKE is higher in the top part of the bed where particle volume fraction is lower and gas volume fraction is higher. It may be concluded that this characteristic might be due to the presence of larger particles since TKE is higher above y/H = 0.25 (expanded bed region).

4.3.3. Particle Volume Fraction Profiles

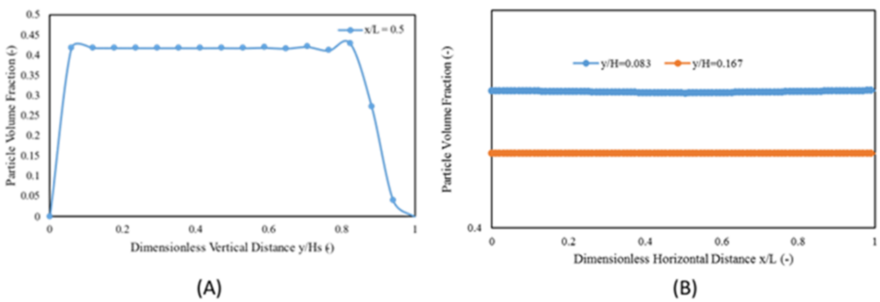

Figure 6. Steady-State Particle Volume Fraction Profiles for 20% mixture, 0.235m initial bed height, and superficial velocity of 0.225m/s (A) Dimensionless Vertical Distance (B) Dimensionless Horizontal distance.

Figure 6 A shows the particle volume fraction profiles over vertical centerline. An important observation is that the particle volume fraction starts decreasing from y/H = 0.8. This confirms the observation in Figure 4A where the particle velocities were higher. Figure 4B shows that the particles volume fraction deviating between 0.4 to 0.42. The particles tend to quickly achieve a volume fraction of around 0.4 at the starting of the bed and shows a decreasing trend from 0.8 < y/Hs < 1. The particles show a peak near the starting of the fluidized bed and similarly near the end of the bed

4.3.4. Turbulent Dissipation Rate Profiles

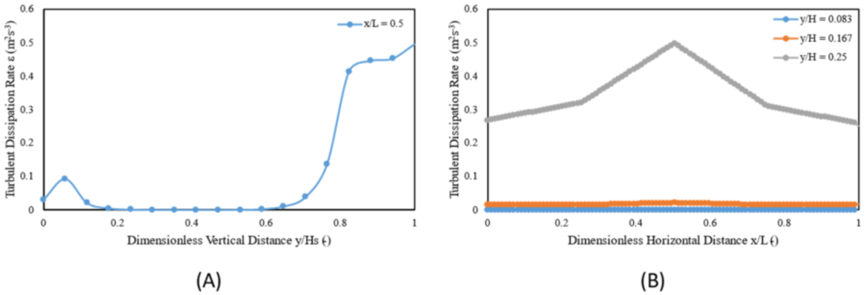

Figure 7. Turbulent Dissipation Rate Profiles for 20% mixture, 0.235m initial bed height, and superficial velocity of 0.225m/s (A) Axial Position (B) Different Radial Positions.

Figure 7A shows the steady-state axial profile for turbulent dissipation rate at the centerline for 20% mixture, 0.235m initial bed height, and superficial velocity of 0.225m/s. Clearly the turbulent dissipation rate mimics the trends shown by turbulent kinetic energy. Figure 7B confirms that part of the energy is dissipated at the bottom of the bed while some part is dissipated in the top expanded bed region.

4.4. Effect of Binary Mixture Composition on Be Characteristics

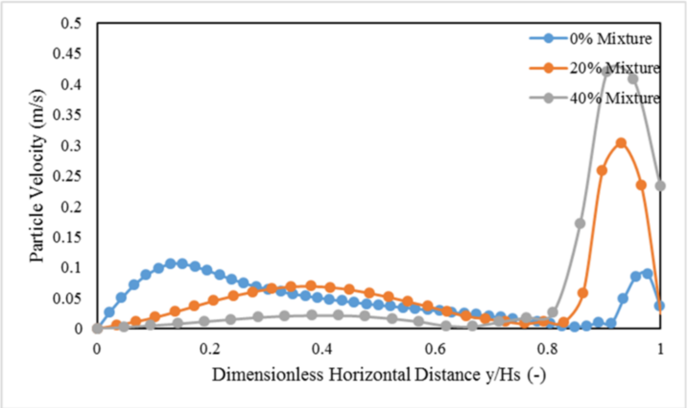

Figure 8. Steady-State Particle Velocity Profiles for 0%, 20% and 40% mixture, 0.235m initial bed height, and superficial velocity of 0.225m/s for Dimensionless Horizontal distance.

Figure 8 (A) shows the steady-state axial profile for particle volume fractions at the centerline for a 0%, 20% and 40% mixture with an initial bed height of 0.235m and 0.225m/s superficial gas velocity. It is important to note that as the amount of large particles increases the particle velocities in the bottom goes down while in the dilute be increases substantially. The segregation of the bed becomes more prominent with increase in the mixture particles at the superficial velocity considered.

5. Conclusion

Interesting characteristics of fluidized bed are observed both in terms of qualitative and quantitative predictions for binary mixtures chosen for the study.

Time averaged steady state flow patterns show increase in bed height with increase in superficial velocities for both binary mixtures considered in the present study

Segregation of the bed is observed for the particular bed height and superficial velocity considered for the study. Both axial and radial profiles of particle velocities (at centerline and three axial positions respectively) show that the particle velocities are higher at the bottom portion of the bed and the dilute portion of the bed

Further, the turbulent kinetic energy and the dissipation energy also confirm that energy is dissipated in the bottom and top of the bed while the middle portion no dissipation takes place

The segregation of the bed is confirmed from the particle volume fractions as well

Another important characteristic at the superficial velocity considered is that the segregation in the bed becomes more dominant in the bottom and middle region of the bed as the composition of larger particles increases from 0% to 40%.

6. Future Work

Three dimentional simulations of the current geometry would be carried out to identify the range of superficial velocities where complete mixing can be obtained for the selected binary system. Further, simulations for other combination of binary mixtures needs to carried out. A systematic study in the above lines would provide guidelines for an operating window for applications using binary systems in Fluidized beds and improve the transport phenomena (heat and mass transfer characteristics) of fluidized beds.

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