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Simulation the hydrodynamic behavior of binary solid-liquid fluidized beds

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Abstract

Solid-liquid fluidized beds containing binary mixture of spherical particles of different size and density has been studied. A combine of Eulerian-Langrangian model is used for predicting the hydrodynamics flow behavior of binary solid-liquid fluidized beds for a range of liquid velocities. The combining takes into account the effect of forces between particle-particle, and particle-liquid. The interaction between the liquid and each particle is performed through a drag force. In this study, three cases (pure species A, pure species B and mixture of pure species A & B) for a range of liquid (water) of fluidization have been investigated in the simulations. The simulations results demonstrate a good stability during the simulation time. The hydrodynamic behaviors for fluidized beds like the bed voidage (porosity), mean particle Reynolds number and bed height are presented as a function of simulation time. The binary solid consider the smaller (denser) component as species A and the bigger (less dense) component as species B, in terms of the bed expansion height and porosity of the fluidized beds at a range of liquid velocities. The analysis of the hydrodynamics in the bed allows to understands the govern mechanisms of mixing and segregation for binary solid system. The comparisons results of each species (A, B) alone with the mixture of species revealed that; the hydrodynamic behavior (bed height, bed voidage and mean particle Reynolds number) of the mixture is less than for species A and species B each one alone, this illustrates and explains the tendency of the mixture to segregate, especially with the increase of the inlet liquid velocity. Thus, the results of combining model prove the effectiveness of the model to predictions the actual system behavior.

1. Introduction

Liquid-solid fluidized beds have been widely used in industry for hydrometallurgical operations, adsorption, crystallization, sedimentation, particle classification, ion exchange and many more depending on the level of disparity due to size and/or density differences. Therefore, it desired to understand, predict and evaluate the hydrodynamics behavior of particle mixing, segregation and desperation which are vital for optimizing the operation and design of liquid fluidized beds units. Binary particle systems consist two types (species) of particles may different in size, density or even shape, can have the tendency to segregate when fluidized with liquid [1]. The collision forces particle-particle and the interaction forces between the particles and the liquid, produce unbalance forces acting on the particles. Another reason that induced the binary particle system to segregate is the convective motion of particles due to the difference in the particle Reynolds number (or terminal settling velocity). As consequence, the particle species (larger or denser) are trend towards the lower region of the bed due to dominate gravitational force. In the other hand, the particle species (smaller or lighter) might flow upwards due to dominate fluid drag force to the upper region of the bed. A considerable progress has been made in the area of hydrodynamic modeling of fluidized beds, this allows of the possibility to improve the computational resources and development of physical models for multiphase interactions. Specifically, combine Eulerian-Langrangian model can be used to provide comprehensive details such as spatial and temporal distribution of local volume fractions of solids and liquid, the intermixing heights of the separate phases particularly in the areas where quantification is difficult. Generally, Eulerian models (continuum approach (Computational Fluid Dynamics CFD)) take into account all phases to be continuous and interpenetrating. The equations employed are a generalization of the Navier-Stocks equations. In other hand, Lagrangian models (Discrete model (Discrete Element Method DEM)) solve the Newtonian equations of motion for each individual particle, effect of collisions forces between particle-particle, and forces acting on the particle by liquid. Various factors like the two solid species properties and fluid properties influence the establishment of equilibrium of forces in the system. The interaction force between fluid and particles (drag force) is balances the gravity acting on the particles, with the effect of buoyancy force in the fluidized bed, which enhances mixing properties. The hydrodynamics of liquid fluidized beds are very complex, which has caused many of problems. Therefore, better understanding and good prediction of particle mixing and segregation behavior are crucial in the design, operation and scale up of the solid-liquid fluidized beds. Many of studies and researches have been carried out to understand the behavior of binary solid particles systems. The limitations of experimental techniques (experimental instrumentations and measurement methodology), the researchers were obliged to based on empirical correlations, which were developed using macroscopic behavior of the liquid-solid flow in fluidized beds. Mathematical models are proposed for predicting the solid concentration profile in binary-solid liquid fluidized beds [2, 3]. In other hand, empirical studies have been made for understand the macroscopic, like the influence of inert particles on liquid-solid mass transfer is studied in fluidized beds by using a binary-mixture of solids of differing size and density [4-8]. In recent years, computational and simulation models have proved effective in reproducing most of the features on both microscopic and macroscopic scales of characterizing the transient behaviors of complex units involving multiphase flows.

In recent years, numerical studies and models have been carried out on binary solid-liquid fluidized beds by using continuum approach (Computational Fluid Dynamics CFD). The continuum approach (CFD) gives very detailed information about the local values of phase hold-ups and their spatial distributions. Such information can be useful in the understanding of the transfer phenomena in fluidized beds. Generally, two approaches are developed and employed in the literatures for CFD modeling in fluidized beds: Eluerian-Eluerian (E-E) and Eulerian-Langrangian (E-L) approaches. The E-E approach can not reveal the information in particle scale, which is essential to the study of the hydrodynamic behavior of binary solid-liquid. The E-L approach on the other hand, can be used to provide comprehensive details in liquid-fluidized beds such as spatial and temporal distribution of local volume fractions of solids and fluid, the intermixing heights of the separate phases particularly in the areas where quantification is difficult. Generally, Eulerian model (CFD) taking into account all phases to be continuous and interpenetrating. The equations employed are a generalization of the Navier-Stocks equations. While, Lagrangian model (DEM) provide the information on each particle (i.e., position, velocity and contact force). The Lagrangian (DEM) model is solve the Newton's equations of motion for each individual particle, effect of collisions forces between particle-particle, and forces acting on the particle by fluid. The collisions forces between particles are described by collision laws, while the interaction force between fluid and particles is expressed by the drag force, which is balances the gravity acting on the particles with the effect of buoyancy force in the fluidized bed. The CFD-DEM simulations have been used for studying the segregation and dispersion of binary particle species of the same or different size with different densities and may even different shape in liquid fluidized beds [9-13]. The limitation of E-L (CFD-DEM) approach is accompanied with high computational as it tracks each individual solid particle.

The objectives of this study are; using a combine of E-L (CFD-DEM) model for examination and prediction of the hydrodynamics macroscopic and microscopic behaviors of binary-solid liquid fluidized beds, for better understanding the segregation and separation of the particles particularly different in size and density is used. The model is using to examine the mechanisms governing mixing and segregation of two solids species (glass (species A) and porous hollow wet char (species B)) differing in size and density. Then, simulations will be used to present the behavior of each solid species alone and for a mixture of glass and porous hollow wet char particles fluidized by water for a range of inlet water velocities. Finally, simulations results will be analyzed, to find out the influence of the liquid velocity, size and density of the mixture on the equilibrium and dynamic degree of mixing and segregation.

2. Methodology and approaches

To obtain governing equations for the solids phase and liquid phase combine E-L model can be used to predict the behavior of binary-solid liquid fluidized beds. The Discrete model (DEM) [14-19] for predicting the particle motion; the trajectories and rotations of individual particles are evaluated based on Newton's 2nd law of motion, using a numerical time stepping scheme. Contact forces are calculated at each time step using appropriate contact laws, and resolved into their normal and tangential components, detailed in [19]. The key assumption in discrete model is that disturbances cannot propagate from any particle further than its immediate neighbors, providing a sufficiently small time step is used. In this study the CFD code is the open source software Code_Saturne, which solves the Reynolds-Averaged Navier-Stokes (RANS) equations for the incompressible flow by employing a finite volume discretization approach. CFD code is based on a co-located finite volume approach that accepts meshes with any type of cell for calculations of the fluid flow, the locally-averaged continuity and Navier-Stokes equations are solved using the SIMPLEC method to give the fluid velocity and pressure [20]. It was chosen to use k-ε model, which largely applied for its simplicity. The transport of the turbulent kinetic energy k and turbulent dissipation rate ε are examples of equations commonly used as closure, leading to the well-known k-ε turbulence model. This CFD calculation is combined with the DEM simulation by carefully applying Newton's 3rd law of motion to the fluid-particle interaction force. The following assumptions were made: the particles are spherical and non penetrable (hard sphere approach); physical properties of two particles species and liquid (water) such density and young modulus are considered to be constant; there are no chemical interactions between the solid phase and the liquid (water).

3. Solid-liquid interaction forces

A good prediction of fluidization stability requires a priori knowledge of the effective forces acting on the particles suspended in the fluid (liquid) medium. Computational models that combine CFD-DEM have proved effective in reproducing most of the features on both microscopic and macroscopic scales of complex units involving multiphase flows. The effective forces acting on a particle placed into an infinite and viscous fluid experiences are; gravity force, buoyant force, and drag force. The drag force depends on not only the relative velocity between the solid particle and fluid but also the presence of neighboring particles, i.e., local volume fraction of solid phase. The drag force is expressed by considering these factors as follows:

$$\vec{F}_{D,i} = \frac{C_{D,i}}{8} \pi \rho_f d_p^2 |\vec{u}_r|^2 \varepsilon^2 f(\varepsilon)^m \tag{1}$$

Where $C_{D,i}$, the drag coefficient d_p is the particle diameter, ε the local porosity, $f(\varepsilon)$ is a porosity function, u_r is the superficial slip velocity between the particle and the fluid and m is a parameter, in this study m=4,75. The local porosity is calculated by Representative Elementary Volume (REV) method is centered on the particle, detailed in [16]. The drag coefficient $C_{D,i}$ on a single sphere is function of Reynolds number of the particle (Re_p), and $C_{D,i}$ is given by Dallavalle (1948) [21]:

$$C_{D,i} = \left(0.63 + \frac{4.8}{\sqrt{Re_p}}\right)^2 , \quad Re_p = \frac{\rho_f \varepsilon u_r d_p}{\mu_f} \tag{2}$$

In other hand, the gravity force is a constant and acts in the downward direction, and the buoyant force is also a constant but acts in the upward direction. The drag force, however, acts against the direction of motion and is a function of the relative velocity between the particle and liquid. Thus according to the condition of equilibrium state;

$$\sum \vec{F}_y = m_i \vec{g} \cdot \vec{i} + \vec{F}_{D,i} \cdot \vec{i} - \vec{F}_{B,i} \cdot \vec{i} = 0 \tag{3}$$

Thus for a single spherical particle ($f(\varepsilon)^{\mathrm{m}} = 1$):

$$\frac{\pi}{6} d_p^3 \rho_p g = \frac{\pi}{6} d_p^3 \rho_f g + \frac{C_D}{8} \pi \rho_f d_p^2 |u_r|^2 \varepsilon^2 \tag{4}$$

Where $\vec{i}$ is unit vector and its direction is opposite of the direction of acceleration due to gravity, $\vec{F}_{B,i}$ is buoyant force and ρ_p represent the density of the particle. Joseph et al. [22] are proposed a relation for each particle's coefficient of restitution taken to be a function of the particle Stokes number in liquid-particle systems, where the collisions particle-particle is differ significantly from those in gas-particle systems due to the effect of hydrodynamic lubrication forces between the particle surfaces which depend on the fluid density and viscosity. Thus:

$$e_{liquid} = e_{gas}(1 - \frac{St_c}{St}) \tag{5}$$

where e_{gas} is the particle coefficient of restitution in air, and St_c is the critical impact Stokes number. In this work, (St_c =10) [22]. The particle Stokes number (St), is given by:

$$St = \frac{Re_p \, \rho_p}{9\rho_f} \tag{6}$$

4. Simulation parameters and operation

The model development used in this work is based on the simulation previously developed for a uniform particle system [6]. For this model, it decided to use a simple case of non-deformable and non-penetrable particles in 2D with the computational software developed in our laboratory, to simulate the binary-solid liquid fluidized beds. The bed is initially filled particles with a (h_o=0.1 m) high is placed in a column (D = 0.1 m and H = 1 m) depicted in Fig.1. A uniform liquid (water) inlet velocity across the base of bed was used in all cases. The bed materials were selected from literature (Moritomi et al. 1982) [23]; glass beads for species A, and porous hollow wet char for species B. The simulations have been done for three cases; pure species A (2500 particle), pure species B (625 particle) and mixture of species A with species B (1563 particle) as depicted in Fig.1.The particle and water properties are detailed in Table 1.

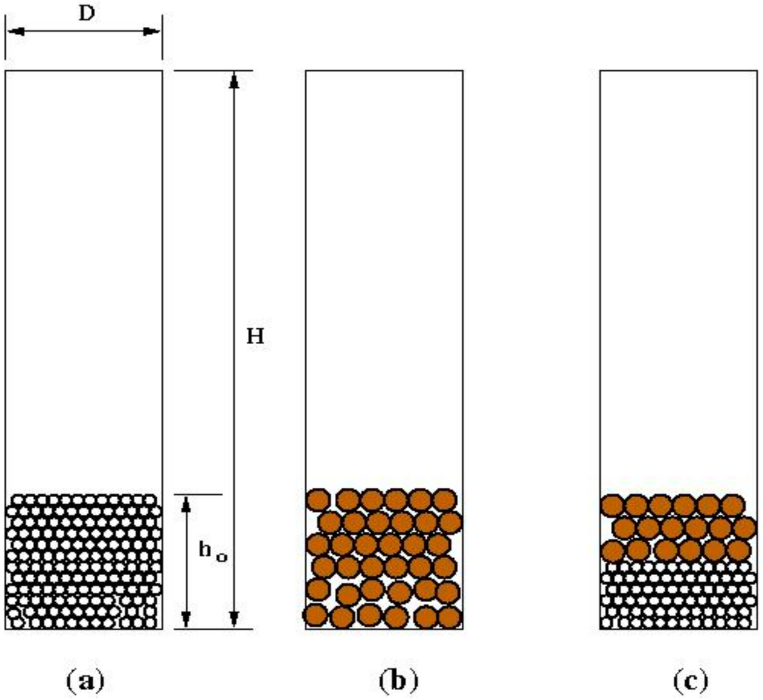


Figure 1: Schematic drawing of 2-D bed; a) pure species A, b) pure species B and c) mixing of species A & species B

Table 1: Physical properties and dimensions of simulated system

Solid phase (mixture)			Fluid phase	
Species	A	B	Water properties	Value
Particle diameter, mm	2	4	Viscosity, $kg.m^{-1}.s^{-1}$	0,001
Particle density, $kg.m^{-3}$	2450	1500	Density, $kg.m^{-3}$	1000
Number of particles for mixing case	2500	625	Bed width, m	0,1
Friction coefficient	0,3	0,4	Bed height, m	1,0
Time step, second	$1x10^{-5}$		Temperature	20 °C

5. Simulation results and discussion

Numerical study was conducted to investigate the mixing and segregation behavior of binary mixtures of particles with different sizes and densities. A house code of a two dimensional DEM combine with three dimension CFD model was programmed to carry out numerical simulations. To obtain the statistically steady state of the solid-liquid two-phase flow, all simulations are continued for 20 s of real simulation time using a time step of $1\text{x}10^{-5}$s, on the workstation Z 230 (3.4 GHz Intel Core i7).

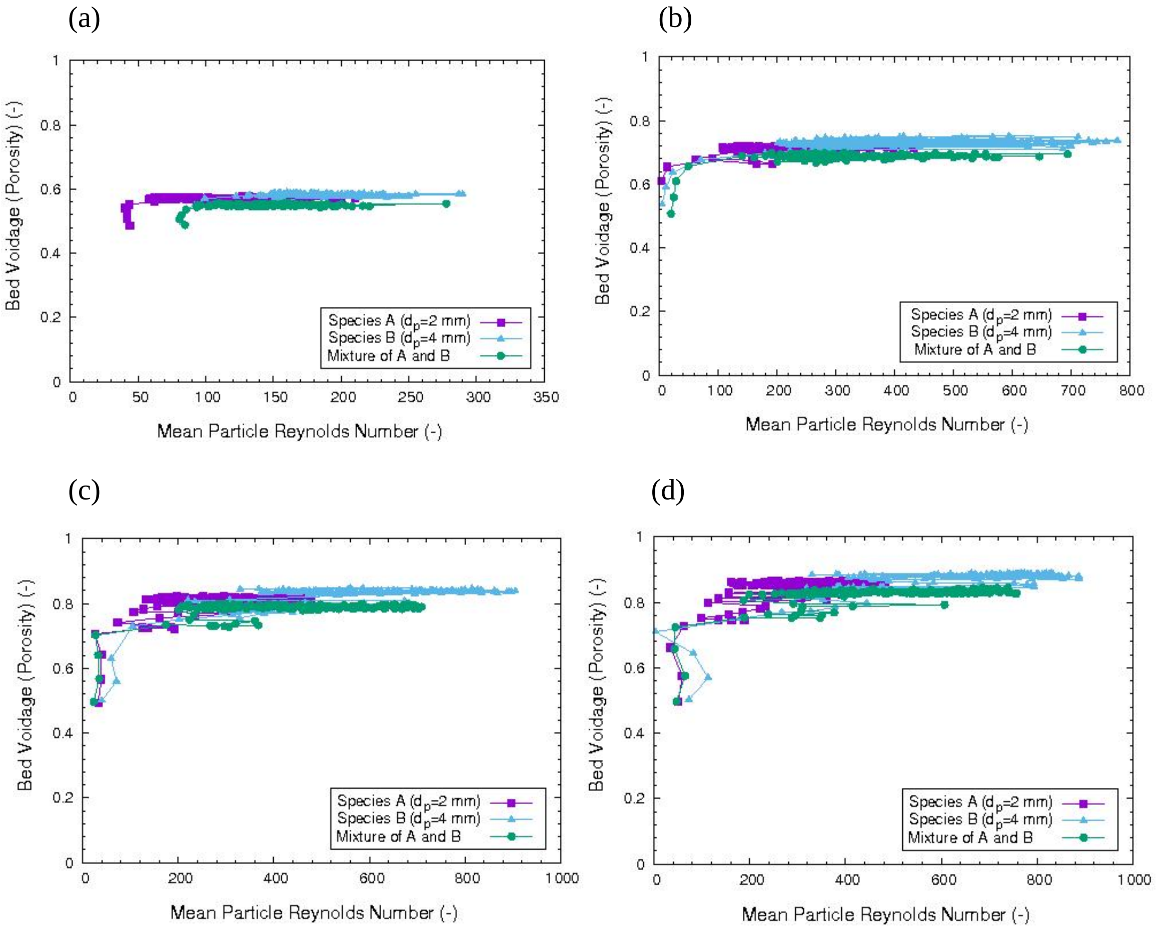


Figure 2: Evaluation of the bed voidage with the mean particle Reynolds number for different velocities of the fluid: a) v_f = 0.04 m/s, b) v_f = 0.08 m/s, c) v_f = 0.12 m/s and d) v_f = 0.14 m/s.

Fig. 2 depicted the bed voidage (porosity) as a function to the mean particle Reynolds number for the three cases (pure species A, pure species B and mixture of pure species A & B) for different water velocities (0.04, 0.08, 0.12 and 0.14 m/sec) of fluidization. Fig. 2 a-d, reveals a good stability of the values of bed voidage with the mean particle Reynolds number during the simulations time and the values of mean particle Reynolds number for particles (pure species A) is less than the values of two other cases because of species A has heavier density (heavier inert particles). Another thing, the values of bed voidage for mixture is less than the values for pure species A and species B, this illustrates and explains the tendency of the mixture to segregate, especially with the increase of the inlet liquid (water) velocity (Fig.2 c, d). The relationship between bed voidage and height for different inlet velocities of the fluid (0.08, 0.10, 0.12 and 0.14 m/s) is shown in Figure 3. Figure 3 a-d shows, the species B has the highest bed height and bed voidage (porosity) as compared with others. In other hand, the hydrodynamic behavior of the mixture (A&B) is less than of the pure species A and pure species B, this confirm that segregation of a binary mixture of particles occurs when there is a considerable difference between their drag per unit weight (see Fig.4). The bed expansion (height) is plotted as a function of simulation time (20 s) for different inlet velocities of the fluid (0.04–0.14 m/s) is depicted in Fig. 5.

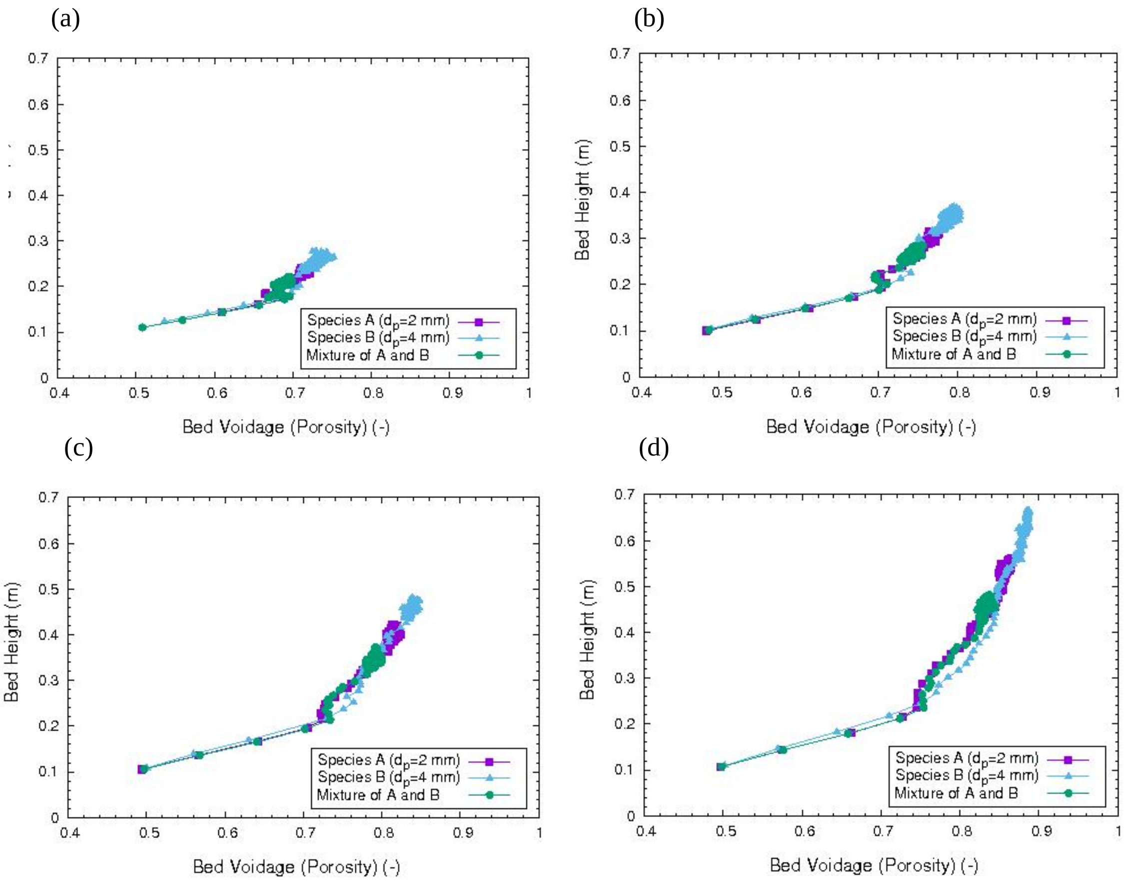


Figure 3: Evaluation of the bed height with the bed voidage for different velocities of the fluid: a) v_f = 0.08 m/s, b) v_f = 0.10 m/s , c) v_f = 0.12 m/s and d) v_f = 0.14 m/s.

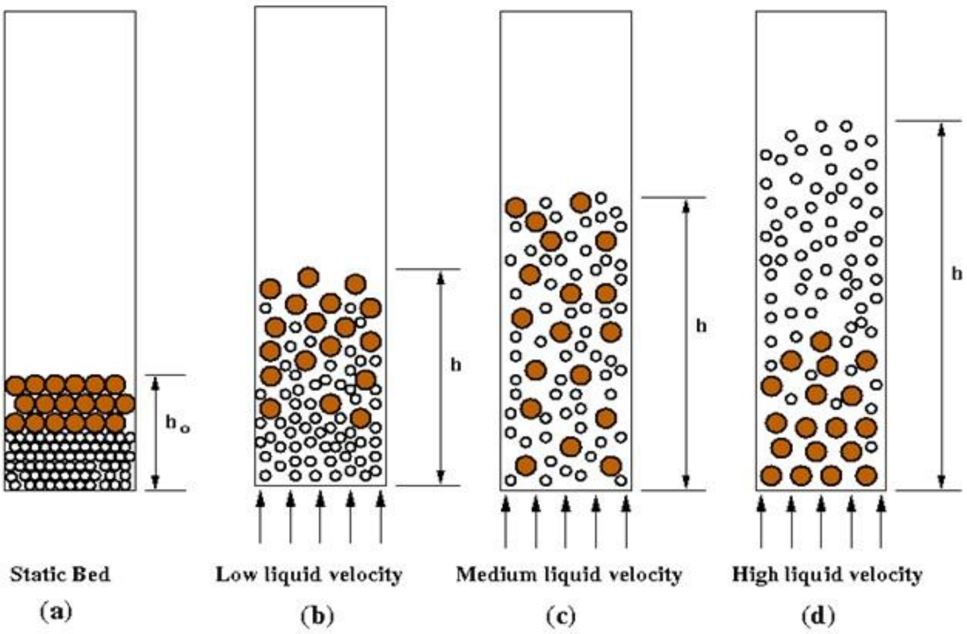
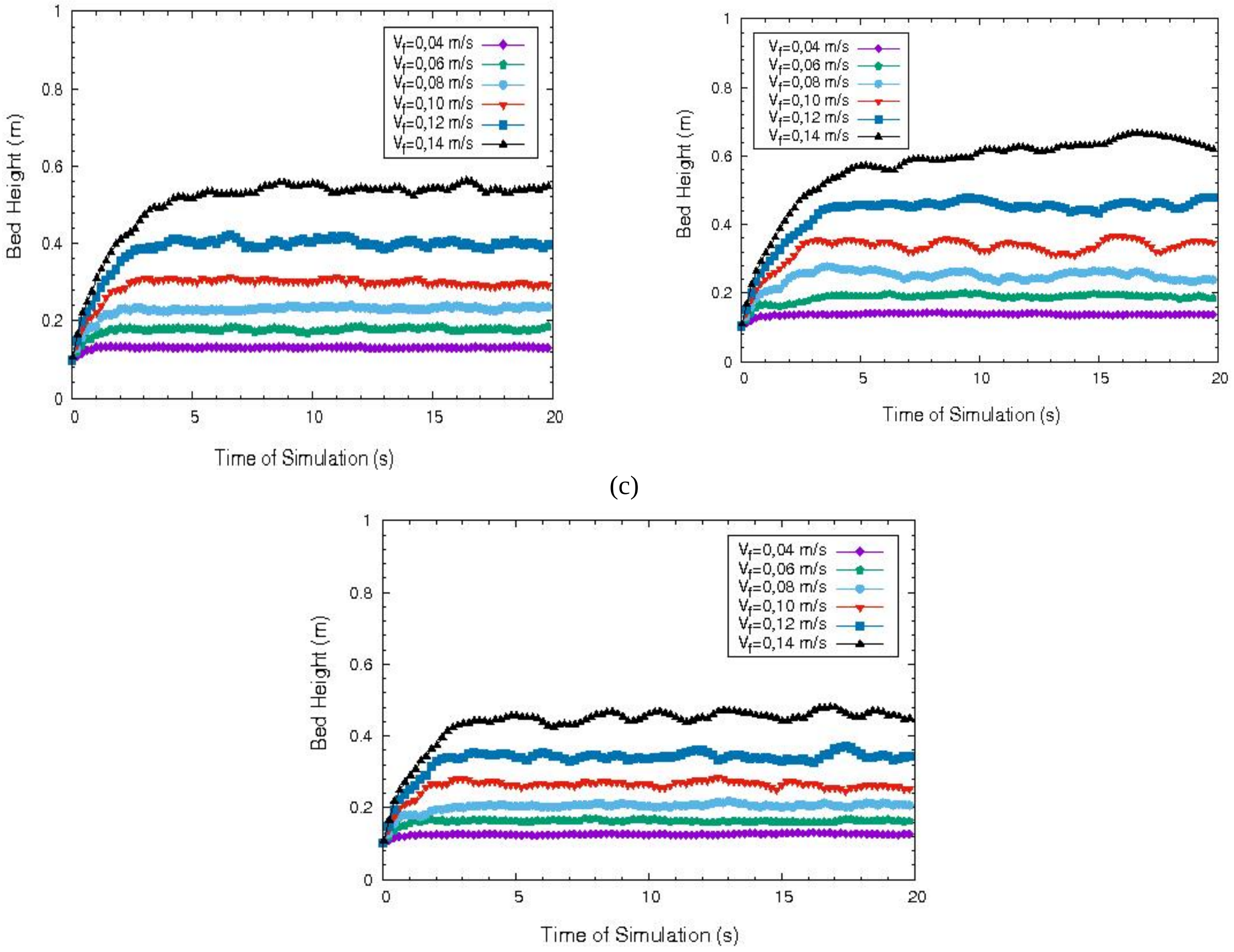


Figure 4: Schematic of solid distribution of binary particle species in a liquid fluidized bed of the stratification and mixing behavior of a binary fluidized bed with increasing superficial liquid velocity [23, 24].

The velocities, obviously all above the minimum fluidization of both solids (species A and species B), are very different from one another and bed expansion from one value to the other is evident. In Fig.5, it can be seen that after about 5 s (except the species B at v_f =0.14 m.s^{-1}) the solid–liquid two phase flow reached the statistically steady state and both particle species fluctuating around a constant value. Fig.5 b shows that the bed height of species B is greater than other two cases, because of low density and large size particles of species B that enhances the buoyant force of these particles. While Fig.5 c (mixture species A&B) shows a good stability and steady state of bed height with the simulation time, but the bed height of less than others accuse the mixing and segregation of the particles.


(a)

(b)

(c)

Figure 5: Evaluation of the bed height with the time of simulation for three cases: a) pure species A, b) pure species B and c) mixture of species A & B.

The simulation results reasonably agreed with the studies data [9-12] in terms of the phenomenal physics of particle segregation and mixing and distribution of solid concentration of each particle species. The simulation results reasonably agreed with the prediction results using existing correlations.

Conclusions

In this study, a combine Eulerian–Lagarangian (CFD-DEM) approach was developed and employed to investigate the mixing and segregation behavior of binary mixtures differing in both size and density. Detailed information on the solid-liquid two-phase flow characteristics (e.g., local interstitial liquid velocity, bed voidage, bed expansion (height), individual particle velocity, mean particle Reynolds number and instantaneous interactions between particles and the liquid phase) has been obtained. Combine CFD-DEM simulation of three cases liquid-fluidized beds of two solids have been carried out, using a drag force model applicable to polydisperse suspensions. Thus, the combine presents the advantage of the capability to model precisely the particle sizes, densities, the fluid properties and underlying physics of the phenomenon of particle segregation and dispersion in a binary. The information provided by discrete model allowed us to analyze also the local particle flow field and particle dynamics in the system. The apparent uniformity of the stably expanded suspension has been shown in the figures. The analysis of the hydrodynamics in the bed allows to understands the govern mechanisms of mixing and segregation for binary solid system. The comparisons results of each species A and species B each one alone with the mixture of species (A&B) revealed that; the bed height, bed voidage and mean particle Reynolds number of the mixture is less than for species A and species B each one alone, this confirm that segregation of a binary mixture of particles occurs when there is a considerable difference between their drag per unit weight and explains the tendency of the mixture to segregate, especially with the increase of the inlet liquid (water) velocity. The simulation results reasonably predict the behavior macroscopic and microscopic of binary-solid liquid fluidized beds. The results are compatible with the results and data in the literatures, in terms of the phenomenal physics of particle segregation and mixing and distribution of solid concentration of each particle species.

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