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Investigation of segregation of large particles in a pressurized fluidized bed with a high velocity gas: A discrete particle simulation

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ABSTRACT

A numerical study on mixing/segregation phenomena in a pressurized fluidized bed with large particles of Geldart D type of binary density but same diameter with high velocity gas was performed by the use of discrete particle simulation. Particle mixtures are composed of spherical particles with 2 mm diameter and 1 g/cm^3 flotsam density and different jetsam densities of 1.25, 2 and 2.5 g/cm^3 with jetsam volume fraction of 0.5. The particles are initially packed approaching perfect mixing state in a rectangular bed and then fluidized by gas uniformly injected at the bottom of the bed. Effect of increase of pressure and density ratio was investigated and mixing/segregation behavior is discussed in terms of flow patterns, solid concentration profile, height variation, pressure drop variation and mixing kinetics. The results show that increase of pressure causes a more vigorous and chaotic motion with more slugs and large bubbles. With increase of pressure, pressure drop and height of the bed increase and both of them fluctuate more with larger amplitude and shorter frequency. Mixing index also decreases with the increase of pressure, and thus solids' mixing diminishes. Effect of increase of density ratio is somehow like effect of increase of pressure in most cases but has a little difference in some cases.

1. Introduction

Particulate systems seem to be widespread in industry and nature. The pattern of their behavior is so convoluted due to the frequent interactions occurring between the individual particles and the interactions that happen between the particles and with the surrounding liquid or gas and wall. There have been a great number of studies aiming at understanding and modeling the behavior of these systems [1]. In the studies, the fluidization system has received a lot of research attention due to its role in industry and its numerous applications.

The fluidization of a bed of particles is carried out through pumping or compressing upwards a liquid or gas at the bottom of the bed through a porous plate. If the flow rate falls below minimum fluidization, the bed will be packed and the particles will be stationary. With the increase of flow rate, the drag force on the particles increases until it reaches balance in their weight for buoyancy. The particles then can move freely, and the bed is called fluidized. When the bed is at fluidized state, it can be stirred and poured like a fluid [2].

Gas fluidized beds are widespread in industry used in different processes that involve physical and/or chemical operations. In fluidized beds, the large specific surface areas of the solids are beneficial for the processes in which there is heat or mass transfer between the particles and gases. Gas–solid fluidized beds produce effective mixing of the two phases resulting in excellent gas–solid contacting and relatively uniform temperature/concentration distributions within the bed. In addition, gas–solid fluidized beds feature a few mechanical parts, as the gas phase gives the energy necessary for fluidization to the particles and encouraging mixing. In many cases, so that all the particles cool, react, and dry similarly, they should be well-mixed, thereby preventing hot-spot formation or agglomeration. Accordingly, fluidized beds are widely used in industry for different purposes such as catalytic reactions, particle coating processes, granulation, heating/cooling, drying, mixing, etc. Fluidized bed coal combustors, biomass fluidized bed gasifier, fluidized bed polymerization, titania synthesis, production of acrylonitrile, and pharmaceutical granulation among many others are some examples of the aforementioned processes [3–8].

Fluidized beds often involve mixtures of solids with different sizes, shapes, and densities. These mixtures of solid particles usually tend to separate during fluidization. The light and/or small particles, called flotsam, accumulate in the top part of a bed and in a fluidized state, while the heavier particles, called jetsam, fall to the gas distributor in a de-fluidized state. Segregation might happen when there is a considerable difference in the drag/unit weight between particles. Those particles that have a higher drag/unit weight go to the surface while the particles with a low drag/unit weight sink to the distributor. The mixing/segregation state of the bed or in other words distribution of

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particles affects bed expansion, mass transfer, heat transfer, and chemical reactions in the fluidized bed. Thus, to improve the performance of these processes, it is necessary to have detailed knowledge about the distribution of the various solid components throughout the bed in different operating conditions. It is of great importance for both industrial operations and research to predict the degree of mixing/segregation of the mixture systems [7,9–11].

Either mixing or segregation might be beneficial, depending on the operation of the bed. Mixing is more important when the chemical reactions take place in the process or when the process control is of great importance. An example of these processes is the chlorination of titanium bearing ore in a gas–solids contact reactor. In these cases, the ore, coke, and gas should be adequately mixed in order to maximize the product and minimize the process times. On the contrary, the segregating process is more important in classifiers where solids are to be separated according to their size or density [12–14].

When the bed is fluidized, a mixing action is produced by the rising bubbles. The wakes of bubbles and their drift actions make the particles go upwards. On the other hand, in the bubble free regions the particles move downwards which results in an overall solids circulation. In binary systems by size or density, this mixing is only reached under particular hydrodynamic conditions. Both the mixing and the segregation of particles are now determined through the upward motion of the same bubbles. Bubbles cause segregation when the denser or larger particles tend to descend favorably through the disturbed region behind each bubble. As the bubble travels up through the bed, particles are drawn into a stagnant zone behind the bubble which is called the wake. When the particles get separated from the wake, the new particles come from the dense surrounding area and this causes the axial mixing. When the bubbles get to the top of the bed, the particles from the wake reach the surface. Through this mechanism, the particles existing in the bottom of the bed might mix with those particles at the top. In the meantime, the bubbles that move up create a void. The particles that descend around the bubbles fill this void. In this condition, the particles that tend to segregate to the bottom only fall rapidly. However, the particles that tend to accumulate at the top of the bed fall more slowly [15]. Also denser or larger particles carried up in the bubble wake from the bottom segregated layer will be shed from the wake and descend rapidly [16]. Rowe et al. [10] believes that particles that have equal density segregate mainly because of their falling through the free space of the bubbles (The mixing/segregation phenomenon has been justified in some other ways by other investigators. See for example: [17–21]. Mixing and segregation occur at the same time, and at equilibrium the outcome of these processes is a concentration gradient in the axial direction while keeping a fairly uniform concentration radially [11,12].

Table 1
Components of forces and torque acting on particle *i* [77].

Forces and torque	Symbol	Equation*
Normal forces contact	$\mathbf{f}_{\mathrm{cn,ij}}$	$-\frac{4}{3}E^*\sqrt{R^*}\delta_n^{3/2}\mathbf{n}$
Damping tangential forces	$\mathbf{f}_{\mathrm{dn,ij}}$	$-\eta_n\left(6m_{ij}E^*\sqrt{R^*\delta_n}\right)^{1/2}\mathbf{v}_{n,ij}$
Contact	$\mathbf{f}_{\mathrm{ct,ij}}$	$-\frac{\mu_s\mathbf{f}_{cn,ij}}{\lvert\boldsymbol{\delta}_{t,ij}\rvert}\left[1-\left(1-\frac{min\{\lvert\delta_{t,ij}\rvert,\delta_{t,ij,max}\}}{\delta_{t,ij,max}}\right)^{3/2}\right]\boldsymbol{\delta}_{t,ij}$
Damping	$\mathbf{f}_{\mathrm{dt,ij}}$	$-\eta_t\left(6m_{ij\mu_s}\mathbf{f}_{cn,ij}\frac{\sqrt{1-\delta_{t,ij}/\delta_{t,ij,max}}}{\delta_{t,ij,max}}\right)^{1/2}\mathbf{v}_{t,ij}$
Fluid drag force	$\mathbf{f}_{\mathrm{f,i}}$	$0.5c_{d0,i}\rho_f\pi R_i^2\lvert\mathbf{u}_i\text{-}\mathbf{v}_i\rvert(\mathbf{u}_i\text{-}\mathbf{v}_i)\varepsilon_i^{1\text{-}x}$
Torque	$\mathbf{T}_{\mathrm{i,j}}$	$\mathbf{R}_i\times(f_{ct,ij}+f_{dt,ij})$
Gravity	$\mathbf{f}_{\mathrm{g,i}}$	$m_j\mathbf{g}$

*where:

$$\frac{1}{R^*}=\frac{1}{R_i}+\frac{1}{R_j},E^*=\frac{E}{2(1-\nu^2)},n=\frac{\mathbf{R}_i}{R_i},\delta_{t,ij,max}=\mu_s\frac{2-\nu}{2(1-\nu)}\delta_n,C_{d0,i}=\left(0.63+\frac{4.8}{\mathrm{Re}_{p,i}^{0.5}}\right)^2,$$

$$m_{ij}=\mathbf{v}_{ij}=\mathbf{v}_j-\mathbf{v}_i+\omega_j\times\mathbf{R}_j-\omega_i\times\mathbf{R}_j,\mathrm{Re}_{p,i}=\frac{2\rho_f R_i\varepsilon_i\lvert\mathbf{u}_i-\mathbf{v}_i\rvert}{\mu_f},\mathbf{v}_{n,ij}=(\mathbf{v}_{ij}.\mathbf{n}).\mathbf{n},$$

$$\mathbf{v}_{t,ij}=(\mathbf{v}_{i,j}\times\mathbf{n})\times\mathbf{n},x=3.7-0.65\exp\left[-\frac{(1.5-\log_{10}\mathrm{Re}_{p,i})^2}{2}\right].$$

Table 2
Simulation and operating conditions.

Simulation No.	Pressure (bar)	Jetsam density (g/cm^3)	Min. fluidization velocity (cm/s)	Superficial gas velocity (cm/s)	Dimensionless velocity (u/u_{mf})
1	20	1.25	22.42	52.42	2.338091
2	30	1.25	16.83	46.83	2.782531
3	60	1.25	9.46	42.19	4.459831
4	20	2	28.06	58.06	2.069138
5	30	2	21.55	51.55	2.392111
6	60	2	12.59	42.59	3.382844
7	20	2.5	31.55	61.55	1.950872
8	30	2.5	23.15	53.15	2.295896
9	60	2.5	14.94	44.94	3.008032

Many experiments have been made to characterize the segregation/mixing of solid mixtures in gas–solid fluidized beds. Rowe and Neinow [22] were among the first researchers who investigated the segregation of binary mixtures with a density difference. Formisani et al. [23] and Wang and Chou [24] investigated the segregation of binary and ternary mixtures as well as the minimum fluidization velocity of poly-disperse systems.

Segregation/mixing behavior of binary mixtures at various gas velocities, initial bed heights, particle size ratios, etc. was investigated by Gilbertson and Eames [25] by the use of the image capturing technique, Goldschmidt et al. [26] using digital image analysis, Jang et al. [27] by analysis of residence time distribution and mixing degree and Sciazko and Bandrowski [28] by use of pressure drop analysis. Gao et al. [9] investigated the segregation of Geldart A and D particles in a turbulent fluidized bed and Zhang and Zhong [29] experimented biomass particles in a 3D fluidized bed. Gauthier et al. [30] analyzed the fluidization behavior of powders with Gaussian, uniform, binary and flat size distribution. Choi et al. [31] investigated the elutriation of coarse particles in the presence of fine particles. Lin et al. [32] investigated the effect of particle size distribution at high temperatures and Noda et al. [33] studied the minimum fluidization velocity of binary mixtures with large size differences. Chenug et al., Chiba et al., and Noda et al. [34,35,33] performed experiments and studied the segregation behavior and minimum fluidization velocity of binary mixtures in bubbling fluidized beds. Nienow et al. [36] experimentally studied systems consisting of particles of equal size, but different densities. Rowe et al. [10] analyzed the segregation in the bubbling fluidized bed consisting of binary

Table 3
Necessary parameters for the simulation.

Bed geometry	2D
Width (m)	0.15
Height (m)	1
Particles	
Diameter	2 mm
Density	
Jetsam (g/cm^3)	1.25, 2, 2.5
Flotsam (g/cm^3)	1
Number	4000
Jetsam	2000
Flotsam	2000
Static bed height (m)	0.108
Gas	
Pressure	Listed in Table 2
Velocity	Listed in Table 2
Simulation	
Grid	15 ∗ 100 or 1500
Total time	50 s for runs where jetsam density is 2.5 kg/m^3 40s for other runs
Time step	10^{-4} s
Restitution coefficient	0.9
Friction Coefficient	0.3
Young's modulus (Nm^{-2})	1.0 ∗ 10^8
Poisson ratio (Nm^{-2})	0.3