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MIXING BEHAVIOR AND HYDRODYNAMIC STUDY OF GASSOLID-SOLID FLUIDIZATION SYSTEM: CO-FLUIDIZATION OF FCC AND COARSE PARTICLES

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MIXING BEHAVIOR AND HYDRODYNAMIC STUDY OF GAS-SOLID-SOLID FLUIDIZATION SYSTEM: CO-FLUIDIZATION OF FCC AND COARSE PARTICLES

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Abstract - Gas-solid-solid (GSS) fluidization system is a unique piece of equipment and its features related to better mixing quality. The mixing and hydrodynamic behavior of FCC particles with coarse particles is investigated in 2D and 3D co-fluidized beds. The reason of enhancing mixing and fluidization properties by adding coarse particles is particularly due to the movement of coarse particles, those breaks the strong interparticle forces between FCC particles and destroy bubble wake (bubble disassociation strategy), time to time. The attrition mass was measured by using Zeeshan relationship at designated conditions.

Keywords: coarse particles, co-fluidization, mixing, bubble wake destruction.

1. INTRODUCTION

Fluidization of gas-solid system is long-standing subject of basic research. As a result of fluid-particle intensive contact, an isothermal system with superior heat and mass transfer abilities favors its use for chemical reactions, mixing, drying, and other applications. Inspire of huge benefits, number of problems are still associated with gas-solid fluidization system. Solid properties, in particular, particle size and size distribution significantly affect the interaction/contacting between particles, their movement and the fluid-particle mixing. Distinct macroscopic phenomena of plug formation, channeling and particle agglomeration was observed with increasing superficial gas velocity in conventional fluidized bed of fine/nano-particles (group C in the Geldart classification) due to strong interparticle forces.

In many cases, a wide PSD is advantageous for better “fluidity. It is well known now that the addition of certain amount of fine particles as the lubricant to a bed of coarse particles tends to enhance particle-fluid contacting and bed expansion. Different empirical index numbers, such as F_{45} (particle fractions smaller than 45 μm) [1], F_{22} (particle fractions smaller than 22 μm) [2], and F_a (a function of fine particle fractions) [3], have been proposed for assessing fine fraction effect on gas-solids mixing and heat/mass transfer.

The concept of powder–particle fluidized bed (PPFB) was first introduced by Kato et al. in early 1990s [4]. It is known to be a useful technique to fluidize group C particles without external aid like acoustic, centrifugal, magnetic, stirring and/or vibrating fields, etc. In the PPFB process, fine powders (group C) are fluidized with coarse particles (group B). The bi-modal fluidized bed system at steady state gives a certain stable hold-up of fine powders in the bed [5]. Many investigators, Sun and Grace [6], and Xue et al. [7] studied bi-modal fluidization in bubbling or turbulent regimes, while, Wei et al. [8] and Du [9, 10] concentrate on CFBs. However, the results were amazingly inconsistent. For example, Sun and Grace reported that the wide size distribution usually gives higher reactor efficiency [6]. The investigation of Xue et al. showed that by adding coarse particles fluidization quality of fine particles could improve [7]. Extensive studies of Wei et al. indicated that the addition of coarse particles to a fluid catalytic cracking (FCC) riser decreased the lateral solids mixing and had insignificant influence on axial solids mixing [8]. Du et al. studied the axial and lateral mixing by using tracer particles of different sizes in a FCC riser and found that the axial solids back mixing increased, while radial solids mixing decreased with the increase of particle size and density. These inconsistent results is a question mark that how PSD influences the hydrodynamics? Experimental evidence is needed for understanding why and how PSD and/or bi-modal system influences the fluidization properties.

In the present exercise, mixing and segregation in bi-modal particles fluidized beds is studied, in order to achieve better mixing and fluidization at lower attrition loss. The circumstances were pictured in 2D and 3D fluidized beds. This study can developed a more nuanced understanding of the bi-modal particles system (co-fluidization of fine with coarse particles) by explaining distinct phenomena of mixing.

2. EXPERIMENTAL

2.1. Materials

In the present work, FCC particles (small) and coarse particles, both are zeolites, provided by Hui Er San Ji Co., Ltd. Beijing, China. The tracer (phosphorous coated R972) small particles were used in 2D fluidized bed in dilute concentration with FCC catalyst particles, in order to maintain their density. The particle sizes

Table 1. Properties of particles used in 2D fluidized bed for mixing berhaviour studies

Particles	Material	Shape	Size (mm)	ρ_{bulk} (g/cm^3)
FCC	Zeo-type + 20% Tracer-Al_2O_3	Spherical	0.07-0.16	2.01
Coarse	Zeo-type	Spherical	1.8-2.2	1.72

distribution of small particles was analyzed using a Malvern Mastersizer (MICRO-PLUS). The physical properties of FCC and coarse particles used in 2D and 3D fluidized beds are listed in Table 1 and 2, respectively.

2.2. 2D Apparatus and method

Fluidization experiments were carried out at room temperature and ambient pressure, at 2D fluidized bed apparatus, shown in Figure 1 (a). The bed was made of plexiglass, having internal width 1.1 cm, expanding segment 32 cm and 50 cm high, cross-sectional area 35.2 cm^2, with a flat perforated plate as distributor. A solids entrainment collection system leads fines outside the bed. The principle of the phosphor tracer technique is demonstrated in Figure 1 (a), where the phosphor particles were excited by a strong flash. The glow of tracer was captured by high resolution digital camera (12 mega pixels) and it can identify the bubble wake braking phenomena and mixing very well. The synchronization of the injection and detection were manually controlled with gas flow rate. Details of the tracer technique have been reported elsewhere [11–19]. Table 2 shows operating details.

2.3. 3D co-fluidization experimental set up

The co-fluidization (binary particles fluidization) experiments were performed in a transparent polymethylmethacrylate (PMMA) column with 5 cm in diameter, 7 holes in distributor, of 0.7 mm and 1 m in height. The pressure drop across the fluidized bed was measured by a U-shape manometer connected to a pressure tap that was placed just above the gas distributor. The bed height was measured by ruler placed at the column wall. Compressed air supplied by a compressor, dried by using silica gel column. Gas flow rate was measured by a series of rotameters. The setup was shown in Figure 1 (b). The operating conditions were tabulated in Table 2 and physical properties of particles are listed in Table 3.

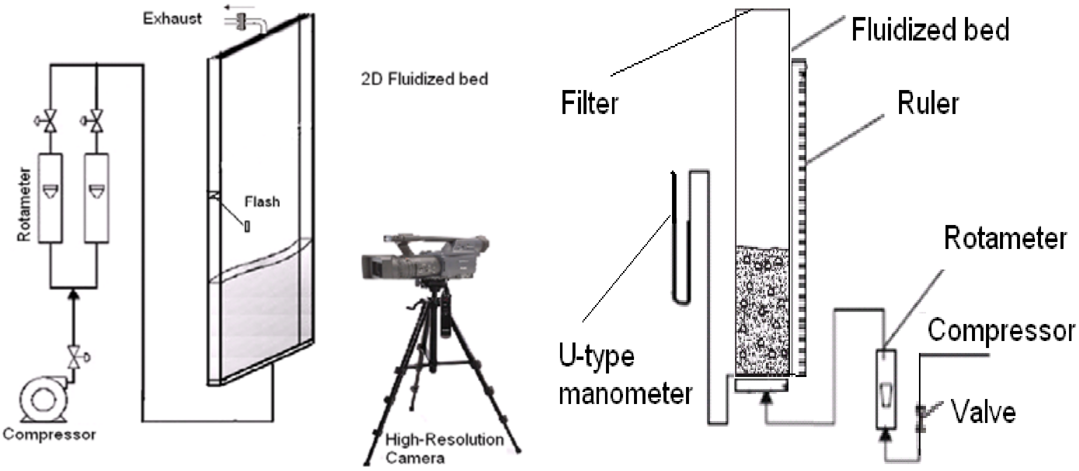

Figure 1. (a) 2D fluidization experimental setup using tracer to absorve mixing phenomena, (b) Fluidization experimental setup of hydrodynamic studies

Table 2. Experimental conditions

Details of 2D studies		Details 3D fluidized bed studies	
Column	32cm x 1.1cm x 50 cm	Column	OD 5 cm and height 100 cm
Distributor	66 holes of 0.5 mm	Distributor	7 holes, each of 0.7 mm
Gas flow rate	0 – 10 m^3/hr	Gas flow rate	0 – 7 m^3/hr
Gas velocity	0 – 1 m/s	Gas velocity	0 – 1 m/s

Table 3. Properties of particles used in 3D co-fluidization hydrodynamic studies

Particles	Material	Shape	Size (mm)	ρ_{bulk} (g/cm^3)	U_{mf} (m/s)	U_t (m/s)
FCC	Zeo-type	Spherical	0.07-0.16	1.68	0.15	0.32
Coarse	Zeo-type	Spherical	1.8-2.2	1.72	0.64	1.39

3. RESULTS AND DISCUSSION

3.1. How fluidization improves in co-fluidization bed?

The formation, breakage and growth of bubbles are definitive for fluidization, heat exchange and mixing efficiency. Fluidization occurs particularly as a result of a dynamic balance between gravitational forces and forces of a fluid through bed. For the systems where the fluidizing particles have significantly different densities and sizes, those create instable local pockets of very high void fraction termed bubbles. This system is known as self-excited nonlinear system. Previously, it is known that periodic perturbation of a system parameter may result in chaos suppression. Here we examine uniform mixing in co-fluidization (GSS), and noted a unique bubble braking phenomena that is principally responsible for uniform mixing. After the formation of bubble, the bubble flow pattern and pressure distribution are sensitive to the block arrangement. Mesh block arrangement in a bed gives high frequent bubbles and low pressure amplitude to the solid bed [20].

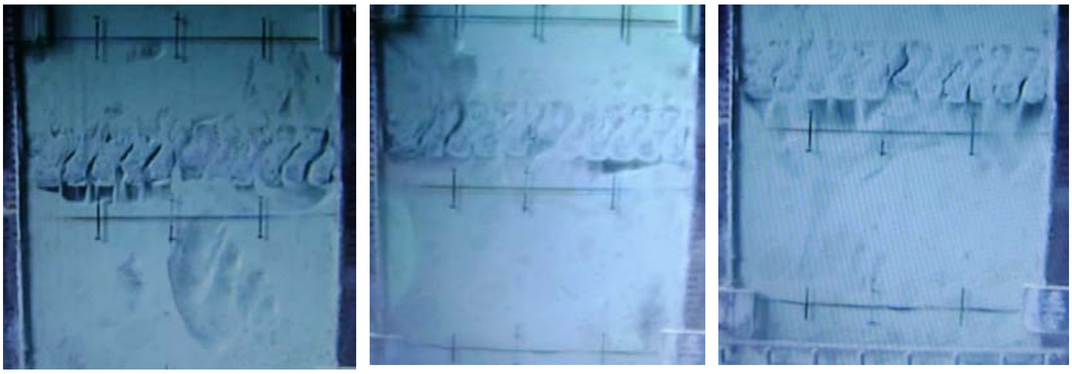

Figure 2. Role of additional distributor in bubble braking

Figure 3. Unique bubble braking phenomena of GSS fluidization

In order to avoid above said circumstances, our group introduced the idea of more distributers at certain height in the bed. The results of additional distributors on flow/bubble are shown in the Figure 2. The installation of second distributer re-divides the bubbles and maintains uniform flow. The propagation of the bubble during rising continually becomes dominant due to the mergence of bubbles, till it bursts out at the surface of the bed. After the bubble bursts, gas void spreads; solid particles in the wake rush up initially, and then settle down. The upper surface was intermittently covered by the defluidized particles which can be swept away during each bubble transit. The phenomena were keenly observed in 2D fluidized bed with or without tracer.

While on the other hand, in bi-modal particle system (GSS FBR) the large bubbles were broken down into small bubbles. This occurs when coarse particles will break large bubble wake's, and generated bubbles give swirl. Momentum was transferred by the bubble to solids in both axial and lateral directions that enhance mixing. The coarse particles produce a high frequency of bubbles and low pressure amplitude around the orifice in comparison with additional distributer, and in ultimate promote smoother fluidization of FCC catalyst with high/uniform mixing. However, coarse particles throughout the bed are in idealistic symmetrical flow, and no jammed was observed. This phenomenon was captured from 2D co-fluidized bed and shown in Figure. 3.

3.2. Hydrodynamics of co-fluidization (FCC particles with coarse particles)

After fundamental description of the role of the bubbles in a bi-modal fluidized bed, hydrodynamic of FCC particles with coarse particles was investigated. On the whole, fluidization properties and mixing was improved. Therefore, here we focus our attention on the overall behavior of the bed. The fluidization of FCC catalyst shows crack formation at low superficial gas velocities. With the increase of the gas velocity to around 0.1 m/s, the FCC particles become fluidizing and their fine counter parts air borne at the upper part of the bed. The experimental results of the pressure drop and bed height ratio, of FCC and coarse particles bed (independently) are shown in Figure 4 (a) and (b), respectively. This is the reason that the bed height ratio of FCC particle is become violent with small increase in velocity. The upper part of bed demonstrates very dilute bed, but in turbulent fluidization behavior. The bed surface was severely disturbed by large gas bubble eruptions and fine particle ejections, which lead to enormous elutriation. While, coarse particles also feel difficulty in fluidization at lower gas velocities, till 0.3 m/s. With the increase of gas velocity, the pressure drop curves do not show a plateau. Figure 4 (b) shows that the expansion of FCC particles bed is much higher than that of the coarse particles bed. This gap can be modified by decreasing the particle size difference. The physical mixture of FCC particles with coarse particles was made in following ratio: The FCC particles were fixed to 100 g, with coarse particles were added as 25, 50 and 75 g. Details about the gross bed behavior, pressure drop and expansion characteristics are shown in Figure 5 (a) and (b). The addition of coarse particles in different quantity to FCC particles has improved the gross fluidization behavior significantly. Furthermore, the minimum fluidization velocity of the mixture decreases. In co-fluidization system, its difficult to measure ΔP across single type of particles (either for small or coarse) as they are well mixed.

3.3. Attrition analysis of co-fluidization

In our previous studies we extensively investigate the mechanical degradation propensity of the zeolite catalysts (particles) in a bimodal distribution environment using a Gas Jet Attrition - ASTM standard fluidized bed test (D-5757). It is observed that when two different types of particles were co-fluidized, the attrition rate of small particles increases, that can be assessed in terms of air jet attrition

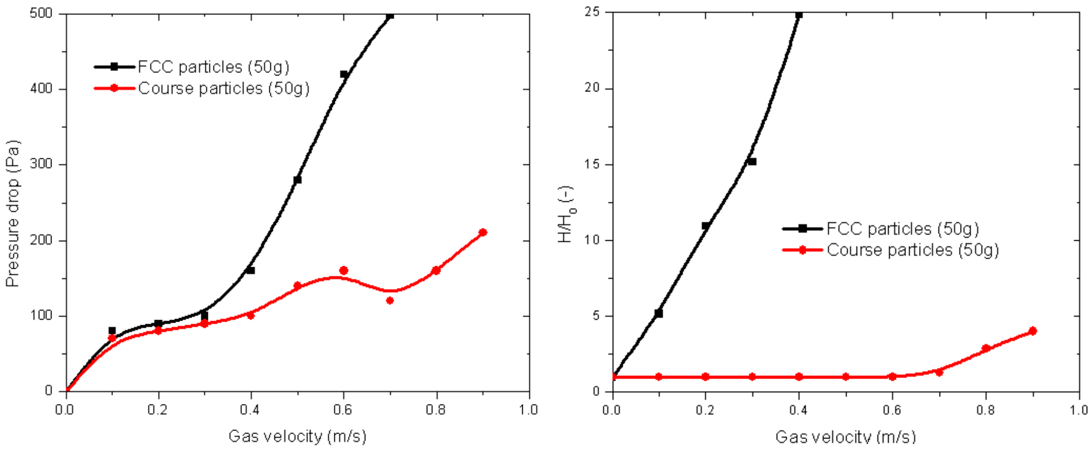

Figure 4. (a) Bed pressure drop curve of FCC and coarse particles, (b) Bed expansion curve of FCC and coarse particles

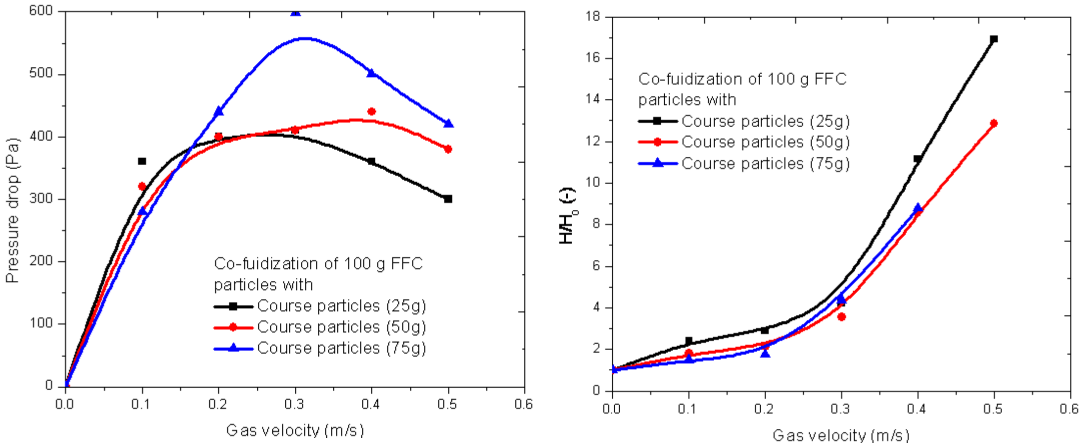

Figure 5. (a) Bed pressure drop during co-fluidization of FCC and coarse particles, (b) Bed expension during co-fluidization of FCC and coarse particles

index (AJI). Experimentation results suggest us that the relative density and particle size ratio have a significant influence on attrition behavior during co-fluidization. A generalized relationship has been drawn, known as Zeeshan relationship, as shown in equation 1 and 2. The formula can be applied to multi-component and/or single component fluidization system of wide size distribution range, in discrete form. Using above Zeeshan relationship we calculate the attrition loss of above discussed system. The results are shown in Table 4. Moreover, it is well understood for analysis, there is the only way to reduce attrition by decreasing relative density and size ratio difference.

Table 4. Estimation of attrition of three co-fluidized beds using Zeeshan relationship (equation 1) and comparison with experimental results (at gas velocity 0.5 m/s)

Material and bed particles		Constants				AJI	Attrition loss by Zeeshan Relationship (g)	Attrition mass after 5 h (g)
FCC (0.1 mm)	Coarse (2 mm)	K	Z	m	e			
100 g	25 g	0.0988	0.4147	0.4340	0.6639	0.022	1.21	1.14
100 g	50 g					0.024	1.21	1.17
100 g	75 g					0.026	1.21	1.20

*K and m is for single particle system while Z and e are Zeeshan's constants for bi-modal system

$$x = Z \cdot t^{e} \qquad (1)$$

Where, $Z = (\rho)^5 \cdot (S)^{0.44} \cdot (K)$ where ρ is relative density of large particles to small and S is the size ratio and $e = 1.53m$. Therefore in a generalized format, by incorporating equation in equation 1, we get equation 2 known as zeeshan relationship [17]:

$$x = (\rho)^5 \cdot (S)^{0.44} \cdot (K) \cdot (t)^{1.53m} \tag{2}$$

4. CONCLUSION

In current study we tried to explore that how bi-modal (G-S-S) fluidization system and how by adding coarse particles enhanced fluidization phenomena. It is found that a unique bubble braking phenomena is responsible for enhancing fluidization properties of bi-modal particle system. The fast mixing behavior is related to the impact of bubble braking impact and swirl, and compared with single particle system. Irrespective of the superior bed holdup in GSS FBR, the added advantage of this system is the uniform distribution of particles; those allow coarse particles to fluidize at lower gas velocities. Finally, the attrition loss was calculated both using Zeeshan relationship and experimentally. It is observed that the attrition loss can be minimized by using same density particles.

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