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Correlation to Predict the Effect of Particle Type on Axial Voidage Profile in Circulating Fluidized Beds

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***Abstract*—**Bed voidage behavior among different flow regimes for Geldart A, B, and D particles (fluid catalytic cracking catalyst (FCC), particle A and glass beads) of diameter range 57-872 μm, apparent density 1470-3092 kg/m^3, and bulk density range 890-1773 kg/m^3 were investigated in a gas-solid circulating fluidized bed of 0.1 m-i.d. and 2.56 m-height of plexi-glass. Effects of variables (gas velocity, particle properties, and static bed height) were analyzed on bed voidage. The axial voidage profile showed a typical trend along the riser: a dense bed at the lower part followed by a transition in the splash zone and a lean phase in the freeboard. Bed expansion and dense bed voidage increased with an increase of gas velocity as usual. From experimental results, a generalized model relationship based on inverse fluidization number for dense bed voidage from bubbling to fast fluidization regimes was presented.

***Keywords*—**Axial voidage, circulating fluidized bed, splash zone, static bed.

I. INTRODUCTION

BED voidage is an important parameter which is responsible of fluidization quality, homogeneous mixing, and process efficiency in the fluidization system [1]. Axial bed voidage in fluidized bed depends on the distribution of the solid particle size and density [2]-[4], the velocity, density [5]-[7], and viscosity of gas, fluidized bed diameter [8] and height [9]-[11], solid inventory and exit geometry of fluidized bed [12]-[14]. So far, many studies on axial solid hold up have been reported [15]-[17]. The increase in superficial gas velocity above the minimum fluidization velocity causes not only increase in flow rate of solids, but flow zone of the solids also changed considerably from bubble, turbulent, and fast fluidized bed to pneumatic transportation, and the entire fluidized bed represents a uniform distribution of solid holdup. Kunii and Levenspiel [18] presented a model which shows that the solid holdup decreases exponentially with the increasing height of the fluidized bed. Li and Kwauk [2] proposed a model for the distribution of the axial solid holdup in fast fluidized bed which represents S shape axial solid holdup distribution structure with a transition zone between a constant lower voidage dense phase and the upper dilute phase. This study was also verified by other researchers [15], [16]. The model of Adanez et al. [11] can be applied in axial direction to obtain the solid hold-up distribution lower than transport disengaging height (TDH). However, there is a need to model the dense bed voidage from bubbling to fast fluidization regime. Although some researchers [2] and [19]-[22] presented correlation for dense bed voidage profile, they dealt with dense bed voidage for a limited particle range and flow regime discretely. For a model relationship to predict the dense bed voidage in fluidized bed based on the system type, operating conditions are important in order to study the fluidized bed behavior. Therefore, the objective of this study is to understand the general relationship between the dense bed voidage and the gas velocity from bubbling to fast fluidization for different particles, and to amend the relationship from Choi et al. [22] for the prediction of dense bed voidage.

II. MATERIAL AND METHODS

The experimental setup consists of a compressor, fluidized bed of 2.56 m-height, 0.1 m-i.d. and 0.01 m thick made of plexi-glass, two cyclones, dipleg, loop seal, and back filter. Particles collected by the primary cyclone were returned to the fluidized bed at 0.7 m from the distributor. The fluidized bed was equipped with 12 differential pressure transducers to measure the axial pressure drop along the riser for the axial voidage profile. Seven different materials which were used in this study are comprised of FCC catalyst, glass beads of different sizes, and particle A. Based on the average mean diameter and apparent density, these materials can be classified as Geldart's type-A, B, and D particles [23] as shown in Table I.

III. RESULTS AND DISCUSSION

A. Axial Solid Holdup

Axial solid holdup was measured by pressure drop across the column using pressure transducers in circulating fluidized bed, and the wall friction and acceleration losses were ignored. An axial solid holdup distribution in column as a function of velocity is shown in Fig. 1 for Particle A. A typical S shape distribution is obtained at transition or splash region between dense and dilute phase. The amount of solid fraction decreases exponentially with the increase of bed height. There is a constant dense phase solid holdup for each velocity observed in the bottom of the column. There is a uniform solid holdup achieved at upper part (freeboard) of the column which is due to the entrained particles at higher velocities for all types of particles.

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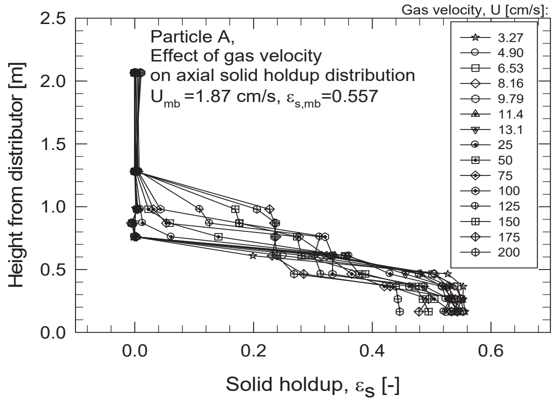

Fig. 1 Axial solid holdup profiles of Particle A with variation of gas velocity.

TABLE I
PROPERTIES OF PARTICLES

Particle	Surface mean particle diameter[μm]	Apparent density [kg/m^3]	Bulk density [kg/m^3]	U_{mb} [m/s]	Geldart's Classification [23]
FCC	57	1470	890	0.0039	A
Glass bead	21	2411	1356	0.0014	A
Glass bead	70	2440	1444	0.0079	A
Glass bead	133	2443	1480	0.0132	B
Glass bead	141	2190	1360	0.0201	B
Glass bead	872	2523	1584	0.50	D
Particle A	55.2	3092	1773	0.0187	A

B. Dense Bed Voidage

Equation (1) is a model relationship by Choi et al. [22], which predicts the solid holdup or dense bed voidage in fluidized beds from bubbling to fast fluidization regime. Plots of (1) by using measured solid holdup for each particle with variation of gas velocity are shown in Fig. 2. It can be seen that there is unsatisfactory agreement between the predicted and experimental solid holdup; hence, (1) should be modified to fit the data more precisely. Based on the trend of experimental data plotted in Fig. 2, by using (1), a new model (2) was proposed for dense bed voidage.

$$\frac{\varepsilon_{s,b}}{\varepsilon_{s,mb}} = 1-(1-\frac{U_{mb}}{U})^{(1.06U_{mb}+1)/1.06U_{mb}} \qquad (1)$$

$$\frac{\varepsilon_{s,b}}{\varepsilon_{s,mb}} = \frac{1}{\left[\frac{1}{\left(\left(U_{mb}/U\right)/\left(U_{mb}/U\right)_{0.5}\right)^{n}}\right]+1} \qquad (2)$$

where U, U_{mb}, $\varepsilon_{s,b}$, $\varepsilon_{s,mb}$, and n are superficial gas velocity, minimum bubbling velocity, dense bed voidage, dense bed voidage at minimum bubbling condition, and a constant factor respectively. $(U_{mb}/U)_{0.5}$ is the cut velocity ratio at which dense bed has 50% ratio of $\varepsilon_{s,b}/\varepsilon_{s,mb}$.

The first step in the calculation of the dense bed voidage from (2) is to get the inverse cut fluidization number $(U_{mb}/U)_{0.5}$ from the experimental data. Fig. 4 depicts these results. It was observed that $(U_{mb}/U)_{0.5}$ increased with U_{mb} linearly with a high correlation coefficient value of 0.999. Then, the next step is to calculate the $(U_{mb}/U)/(U_{mb}/U)_{0.5}$ ratio for each particle at every velocity. Factor "n" in (2) was calculated by regression analysis and was plotted as a function of U_{mb} in Fig. 5 for all the particles mentioned in Table I. The value of n also increased with the increase in U_{mb} for all particles with a correlation coefficient value of r=0.9340. By using n values in (2), a new voidage profile is obtained in Fig. 3. It is apparent that the new amended equation fits the data more precisely than (1).

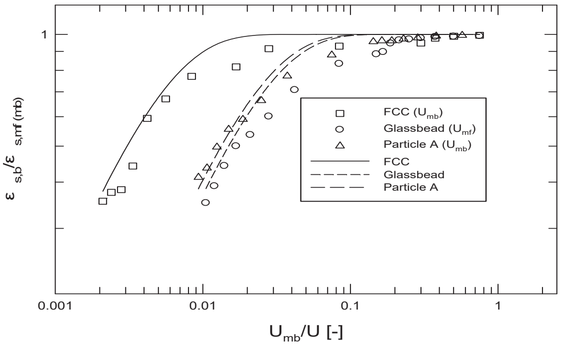

Fig. 2 Comparison of measured dense bed solid holdup (symbols) with (1) (lines)

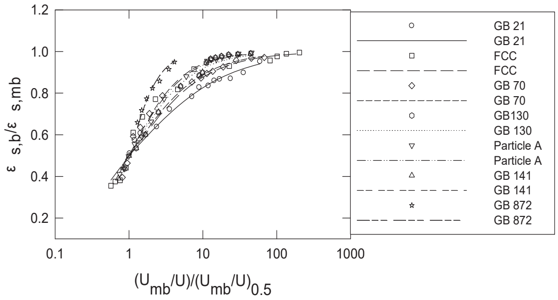

Fig. 3 Comparison of measured dense bed solid holdup (symbols) with (2) (lines)

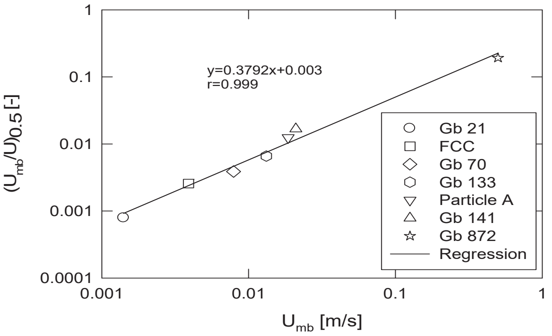

Fig. 4 Inverse cut fluidization number as a function of minimum bubbling velocity

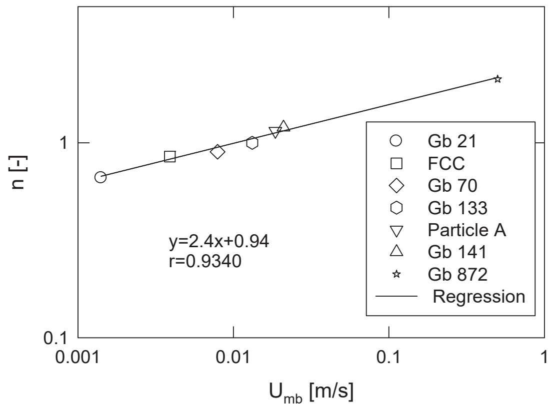

Fig. 5 Factor n of (2) as a function of minimum bubbling velocity

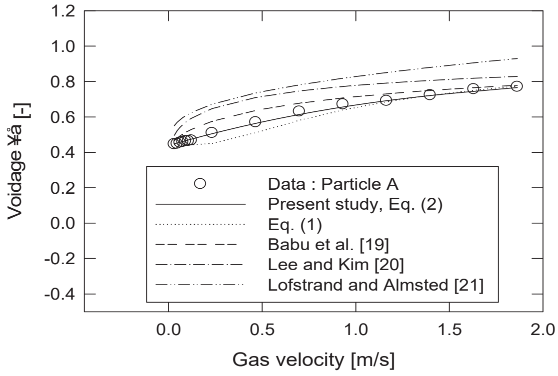

Fig. 6 (a) Comparison of measured dense bed voidage (symbols) with correlations (lines) [19]-[21]

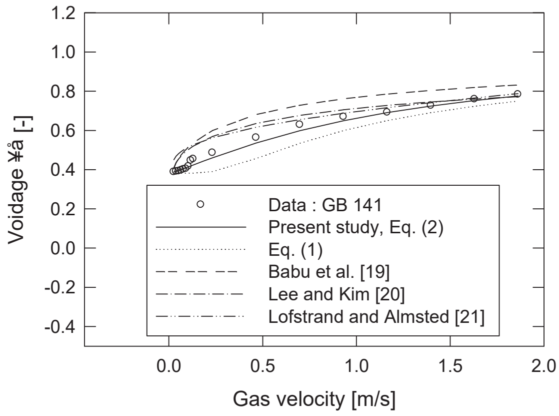

Fig. 6 (b) Comparison of measured dense bed voidage (symbols) with correlations(lines) [19]-[21]

Figs. 6 (a) and (b) show a comparison between experimental dense bed voidage and the one which is predicted by otherauthors [19]-[21]. As can be seen, the predicted dense bed voidage from the other authors are higher than those obtained by (2) which gives a good fit of experimental results for this study.

C. Effect of Static Bed Height

The effect of initial static bed height on dense bed voidage was observed for glass bead 70 and 133 microns for bed heights of 60 cm, 70 cm, and 80 cm. It was found that static bed height has negligible effect on dense bed voidage as can be seen in Figs. 7 (a) and (b). Equation (2) was successfully applied with the same value of n for all three bed heights of both particles.

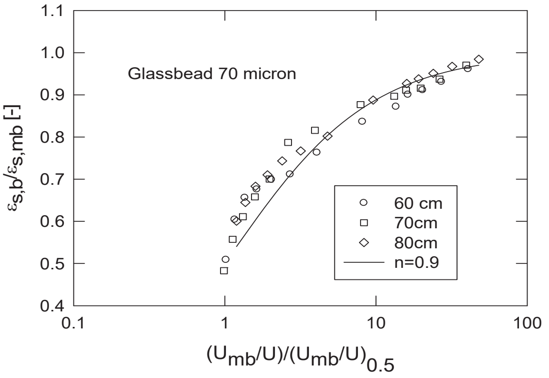

Fig. 7 (a) Dense bed voidage of different initial static bed height

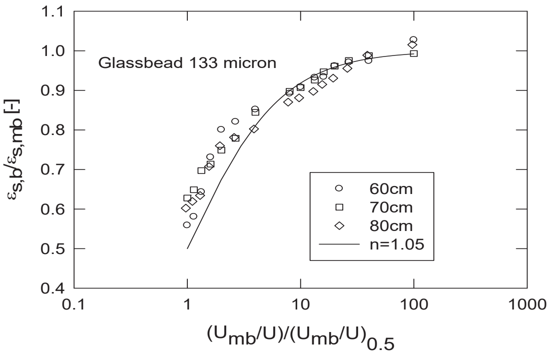

Fig. 7 (b) Dense bed voidage of different initial static bed height

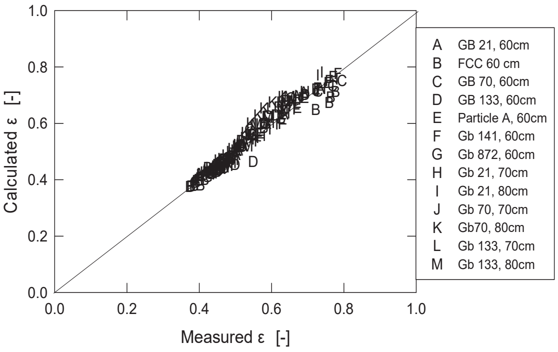

Fig. 8 Comparison between measured dense bed voidage and calculated from (2)

The measured dense bed voidage of different particles at different static bed height was compared with the dense bed voidage calculated by applying new amended (2) in Fig. 8. As it is clear from the figure, a good overall agreement between predicted and experimental data is found.

IV. CONCLUSION

A constant dense bed zone was observed at the bottom of the column which decreases with the increase in superficial velocity. Based on the experimental results, a model relationship of Choi et al. [22] has been modified, and trend of the dense bed voidage can be described successfully by this amended relationship. The bubbling velocity of Geldart group C particles can also be determined by the present new relationship. According to the changes in flow rate and particle characteristics, the bed voidage from the new (2) was found to be in good agreement with the experimental results. Dense bed voidage has been found unaffected by the static bed height.

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