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NONHOMOGENEITY IN A LIQUID-SOLID FLUIDIZED
BED OF SMALL PARTICLES

Final Report

By
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Work Performed Under Contract No. AC22-83PC61004

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Nonhomogeneity In A Liquid-Solid
Fluidized Bed Of Small Particles

Final Report

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ABSTRACT

Experiments were conducted to study the bed behavior of a 2-dimensional liquid-solid fluidized bed of small particles. The bed behavior covered includes voidage distribution, voidage fluctuation, liquid void distribution, and particle velocity distribution. The photographic method was employed to determine the bed behavior.

I. Introduction

Liquid-solid fluidized beds involving small sizes of particles are important to industrial operation, e.g., crystallization and mineral processing. The intrinsic bed behavior such as local voidage, particle velocity and their distributions would govern the performance of a liquid-solid fluidized bed as a reactor. Little information, however, is available regarding this behavior in the liquid-solid fluidized bed, especially for small particle sizes.

Local voidage distributions in a liquid-solid fluidized bed were investigated by Volpicelli et al (1966) using a two dimensional bed. The depth of the bed was approximately one particle diameter. In their experiment, steel aluminum and plastic beads, with diameters varying from 2.86 to 3.18 mm, were used as fluidized particles and water and glycerine were used as the fluidizing liquid. The local voidage distributions were found to be highly dependent on the distributor design. Furthermore, the variance of the local voidage distribution in the steel-water system is larger than that in the aluminum-glycerine system for a given average bed voidage. Jackson (1963), Anderson and Jackson (1964) and Anderson and Jackson (1969) studied the theoretical stability of a uniform fluidized bed subject to small perturbation. They concluded that the growth rate of a small disturbance or a small bubble in a gas-solid system is generally greater than that in a liquid-solid fluidized system. Based on a still photograph of a bubble in a lead shot-water system, Reuter (1966) indicated that there are no fundamental differences between the bubbles in a gas-solid fluidized system and in a liquid-solid fluidized system. Latif and Richardson (1972)

conducted an experiment in a three dimensional bed using 6.16 mm soda glass particles fluidized with dimethyl phthalate solution which has the same refractive index as soda glass. They presented the distribution of particle velocities including tangential, axial, and radial, velocity and total speed from cine films.

This paper is intended to study such bed behavior as voidage distribution voidage fluctuation, liquid void distribution, and particle velocity distribution in a liquid-solid fluidized bed containing small particles, defined as a size of approximately 1 mm or smaller. Comparison of the bed behavior for small particles will be made with that for large particles.

II. Experimental System

II-1. Apparatus and Procedure

The schematic diagram of the experimental apparatus is shown in Fig. 1. A Two-dimensional fluidized made of glass was used for the experiments. The bed is 40.0 cm in height, 11.8 cm in width and 0.186 cm in depth. A 100-mesh brass wire screen was used at the base of the two-dimensional bed to support the bed materials. The calming section of the experimental system consists of two beds: a packed bed located at the bottom and a semifluidized bed located at the top. The length of each of the beds is 20 cm. The semifluidized bed is formed when a fluidized bed is in series with a fixed bed within a single containing vessel. The presence of the semifluidized bed was essential in the experimental design to the establishment of a uniform liquid distribution at the inlet of the liquid-solid fluidized bed. Liquid

uniformity was achieved by establishing a certain fixed bed depth distribution in the semifluidized bed through adjusting liquid flow rate up and down before reaching a desired liquid flow rate. Without a semifluidized bed, liquid-solid vortices would form at the lower portion of the liquid-solid fluidized bed. Liquid uniformity, however, was difficult to achieve at low liquid velocities corresponding to a voidage less than 0.65. The particles used in the semifluidized bed were the same as those in the liquid-solid fluidized bed. Water was used as the liquid phase in the experiment.

Glass ballotini spheres of narrow size distribution were used in the experiments. The physical properties of the glass beads are shown in Table 1. Approximately 100 colored particles were used as tracer particles in the experiments for determining the particle velocity distribution.

The bed was illuminated by two 500W light photo bulbs placed in front of the bed 15 cm apart. A high speed camera equipped with a zoom lens was used to take the motion pictures. The speed used was 64 frames per second. The standard viewing areas in the bed for photographing using the still camera and high speed camera in this study were 6 cm x 5 cm and 4.5 cm x 3.5 cm, respectively.

The void fraction distribution in the bed was determined by counting the number of particles present in a unit volume 0.3 cm x 0.3 cm x 0.186 cm based on a still photograph. Data obtained covered the entire bed volume. It was, however, difficult, if not impossible, to count particles at low bed voidages due to the fact that the particles were too dense to be identified individually. This was especially true for the smallest particles used in the experiments, i.e., 563 μm glass beads.

III. Results and Discussion

III-1 Voidage Distribution

The results of analysis of still photographs are shown in Figs. 4 and 5. Figure 4 illustrates the distribution of local voidage for 797 μm glass sphere. Recognizing that the variance of the local voidage distribution is negligibly small at the minimum fluidization velocity and at the particle terminal velocity, a maximum variance should exist at a liquid velocity between these extremes. Figure 4 reveals that the maximum variance for local voidage distribution exists at the liquid velocity corresponding to an average bed voidage between 0.65 and 0.80. The distribution of local voidage can be well represented by a normal distribution function given below:

$$P(\epsilon) = \frac{1}{\sqrt{2\pi}\sigma} \exp \{-(\epsilon - \epsilon_{av})^2/2\sigma^2\} \quad (1)$$

where

$$\sigma^2 = \frac{1}{N-1} \sum_{i=1}^N (\epsilon_i - \epsilon_{av})^2 \quad (2)$$

Figure 5 shows the voidage distribution for three sizes of glass beads, i.e., 563 μm , 797 μm and 1046 μm . It is seen that the increase in the particle size increases the variance of the distribution at a given average voidage. This finding is consistent with that reported by Volpicelli et al., (1966) in which the variance of the voidage distribution increases when Reynolds number, defined as $d_p U_t^* \rho_L / \mu_L$ where U_t^* is the particle terminal velocity in a 2-dimensional bed, increases. In their experiments, large particles with the same diameter (3.18 mm) but different density were used.

III-2 Voidage Fluctuation

The void fraction fluctuation with time at a given location in the bed for 797 μm and 1046 μm glass beads are shown in Figs. 6 and 7, respectively. In Fig. 6, voidage fluctuations were measured at two different bed locations for the system of 797 μm glass beads. The lower portion of Fig. 6 which was obtained at the location $(x,y) = (0.45 \text{ cm}, 2 \text{ cm})$ shows much larger fluctuation than the upper one which was obtained at the location $(x,y) = (0.45 \text{ cm}, 9 \text{ cm})$; note that x and y represent the axial and radial coordinates with the mid-point of the bed base as the origin. The results also indicate that at the region near the distributor of the bed, the particles are less uniformly distributed than at the region near the upper part of the bed. The value of (x_0, y_0) used for Fig. 6 was (5.9 cm, 10 cm) where x_0 and y_0 represent half width of the bed and expanded bed height, respectively. Figure 7 illustrates the voidage fluctuation for 1046 μm glass beads at two different expanded bed heights, 9.3 cm and 12.5 cm corresponding to two different average voidages, 0.75 and 0.81, respectively. Comparing the two plots in Fig. 7, it appears that the amplitude of voidage fluctuation at the lower average voidage $\epsilon_{av} = 0.75$ is slightly larger than that at the higher voidage $\epsilon_{av} = 0.81$. This result appears to reflect those shown in Fig. 4 for a particle size of 797 μm in that the variance of local voidage distribution is larger at $\epsilon_{av} = 0.80$ than at $\epsilon_{av} = 0.75$. Comparing the upper plot in Fig. 6 with the upper one in Fig. 7, it is noted that the fluctuation for larger particles is more pronounced. This observation appears to reflect the finding shown in Fig. 5, where the local voidage distribution of larger particles exhibits a larger variance.

Based on Figs. 6 and 7, the periodic variations of the void fraction occur at any given location in the bed. These variations can be approximated by a sinusoidal function with a period of 0.3 sec. Careful observations of cine films also show that a wave form of bulk density propagates continuously in the bed. These phenomena have been reported for a deep three-dimensional liquid-solid bed by Anderson and Jackson (1969). In a theoretical treatment of uniform fluidization, Jackson (1963, 1964) has stated that a bed is always unstable in the sense that small disturbances in the distribution of particles will rise through the bed and will become more pronounced as they rise. He indicated that wave propagation requires a deep bed. However, as seen in the present shallow two-dimensional bed, where the ratio of expanded bed height to bed width only equals approximately one, the propagation of disturbances through the bed still occurs.

III-3. "Liquid Void" Distribution

As shown earlier, particles are not evenly distributed in the liquid-solid fluidized bed. Thus, some portions of the bed have a higher bulk density than other portions of the bed. There are a large number of liquid cavities which contain no particles inside. These liquid cavities are denoted as "liquid void". The liquid void does not behave as bubbles in a gas solid fluidized bed or voids in a lead shot-water fluidized bed observed by Retuer (1966). Most liquid voids observed in the present study were in a "tongue" shape. Figure 8 illustrates the distribution of the ratio of the "liquid void" area to the cross sectional area of a particle. "Liquid void" determination involves projecting still photographs on a white paper

attached to a screen. The cavity or "liquid void" is then identified and determined by cutting the portion of the paper containing the void and weighing it. In the case of 797 μm glass beads, some errors may occur using the photographic technique as two particles may partially overlap along the depth of the 2-dimensional bed. This occurs only at a low liquid velocity. The overlapping effect can be neglected, however, at a high liquid velocity. Figure 8 shows the average area of liquid void increases as the average bed voidage or the liquid velocity increases.

III-4 Particle Velocity Distribution

The particle velocity distributions for the entire bed are shown in Figs. 9-13. The distributions of x- and y-velocity components for 797 μm glass spheres are illustrated in Fig. 9 and Fig. 10, respectively, for an average voidage, $\epsilon_{av} = 0.67$. The distribution of x- and y-velocity components can be well expressed by a normal density function similar to that of axial, radial and tangential velocities in the three-dimensional bed reported by Latif and Richardson (1972). The dash curves in Figs. 9 and Fig. 10 represent the normal density functions of the following form

$$P(V) = \frac{1}{\sqrt{2\pi V_i^2}} \exp \left(-\frac{V_i^2}{2V_i^2} \right), \quad i = x, y \quad (3)$$

where $\overline{V_i^2}$ is the mean square velocity. For the total speed distribution, the density function is employed which follows that for the distribution of molecular velocity in gases (Latif and Richardson, 1972). In a two-dimensional bed, the density function of the total speed can be given by:

$$P(V) = \frac{2}{V^2} V \exp \left(-\frac{V^2}{V^2} \right) \quad (4)$$

or

$$P(V) = \frac{\pi}{2(\bar{V})^2} V \exp \left\{ -\frac{\pi}{4(\bar{V})^2} V^2 \right\} \quad (5)$$

Equations (4) and (5) are expressed in terms of mean square velocity and average speed, respectively.

The density functions for the total speed based on the experimental values of $\overline{V^2}$ and $\bar{V}$ are shown in Fig. 11 for an average voidage of 0.67. It is seen that both density functions, i.e., Eqns. (4) and (5), give rise to similar results. Similar distributions for x, y-velocity components and total speed were also obtained for other average voidages and size of particles. Figures 12 and 13 are examples of total speed distribution at the average voidages of 0.75 and 0.80, respectively, for particles of 797 μm . Average speeds of absolute x, y-velocity components and total speed are plotted against liquid velocity for glass beads of 797 μm in Fig. 14. It is seen that as the liquid velocity increases, each velocity component increases linearly. The same behavior is also observed for the other sizes of glass beads used in this study.

Figures 15 and 16 show the variation of the mean square velocity and average total speed, respectively, with the average void fraction for various particle sizes. It can be seen that for a given large average voidage, large particles possess higher velocity or speed than do the smaller particles. Clearly, the fluctuation of local liquid velocity due to the presence of large particles have contributed significantly to the particle size effect shown in Figs. 15 and 16.

Nomenclature

P	density function
U	liquid density
U_t	particle terminal velocity in 3-D bed, cm/s
U_t^*	particle terminal velocity in 2-D bed, cm/s
V	total speed = $\sqrt{V_x^2 + V_y^2}$, cm/s
$\bar{V}$	average total speed, $\Sigma V/N$, cm/s
$\overline{V^2}$	mean square velocity $\Sigma V^2/N$, (cm/s) ²
V_x	x-velocity component, cm/s
V_y	y-velocity component, cm/s
x	x coordinate, cm
x_0	half width of the 2-D bed (5.9 cm), cm
y	y-coordinate, cm
y_0	expanded bed height, cm

Greek Letters

ϵ	local void fraction
ϵ_{av}	average void fraction
ρ_s	particle density
σ	standard deviation

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Table 1 Physical properties of glass beads

diameter, d_p (μm)	density, ρ_s (g/cm^3)	terminal velocity in 2-D, u_t^* (cm/s)	terminal velocity in 3-D, u_t (cm/s)
563 ± 37	2.83	9.70	10.1
797 ± 50	2.83	13.0	14.3
1046 ± 50	2.88	15.4	19.6

Figure 1. Schematic Diagram of Experimental Apparatus.

$$\epsilon_{av} = 0.80, 797 \mu\text{m}$$

$$\epsilon_{av} = 0.75, 797 \mu\text{m}$$

Figure 2. Still Photograph of the Solids Distribution in the Bed.

$$\epsilon_{av} = 0.75$$
$$797 \mu\text{m}$$

Figure 3. Cine Photographs of the Solids Distribution in the Bed.

Figure 4. Distribution of Local Void Fraction in the Bed for Glass Beads of 797 μm .

Figure 5. Distribution of Local Void Fraction in the Bed for Glass Beads of 1046 μm .

Figure 6. Local Void Fraction Fluctuation with Time for Glass Beads of 797 μm .

Figure 7. Local Void Fraction Fluctuation With Time for Glass Beads of 1046 μm .

Figure 8. Distribution of Liquid Void for Glass Beads of 797 μm .

Figure 9. Distribution of x Velocity Components for Glass Beads of 797 μm .

Figure 10. Distribution of y Velocity Component for Glass Beads of 797 μm .

Figure 11. Distribution of Total Speed for Average Void Fraction of 0.67 for Glass Beads of 797 μm .

Figure 12. Distribution of Total Speed for Average Void Fraction of 0.75 for Glass Beads of 797 μm .

Figure 13. Distribution of Total Speed for Average Void Fraction of 0.80 for Glass Beads of 797 μm .

Figure 14. Relationship Between Average Speed and Liquid Velocity for Glass Beads of 797 μm .

Figure 15. Relationship between Mean Square Velocity and Average Fraction for Various Particles.

Figure 16. Relationship Between Average Total Speed and Average Void Fraction for Various Particles.