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Particle velocities in quasi two-dimensional water fluidized beds of spherical particles

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ABSTRACT

Particle velocities have been measured in two-dimensional water fluidized beds of mono-sized spherical glass particles $d_p = 1.94$, 2.98, 4.00 and 6.00 mm in diameter. For each particle size, a separate column was constructed in a manner that the column thickness corresponded to approximately 3 particle diameters. A large number of observations are required to obtain a stable value of total particle speed. The presented data indicated that in order to obtain a stable value of the mean total particle speed, a minimum of 4000 data points was needed. The distribution of total particle speeds follows the Maxwell distribution quite well. The effect of water velocity on the distribution function was similar to the effect of temperature on molecular speed distribution in the kinetic theory. The distribution of vertical and horizontal particle velocity components followed approximately a modified Gaussian distribution. A correlation for predicting the total mean particle speed in 2D water fluidized beds is proposed. The mean absolute deviation between the experimental and measured particle velocities for the present data is 11.0%. The proposed correlation predicts the data of Carlos and Richardson [5] and Latif and Richardson [6] for 3D fluidized beds reasonably well.

1. Introduction

Liquid–solid fluidized beds are used in many processes, such as solids separation and classification, adsorption, ion exchange, catalytic cracking, hydrometallurgical operations, wastewater treatment, heat transfer operations and biotechnological processes [1]. Although there is abundant literature about liquid phase fluidized beds, there is insufficient quantitative information about particle flow patterns as well as mixing and circulation patterns of solid particles, although these quantities are all very important for the estimation of heat and mass transfer rates [2]. Particulately, there are no models or correlations for the prediction of mean particle speed as a function of system properties. Probably the reason for this lack of correlations is that the particle motion is random at any point in the bed so that a large number of observations are needed for an accurate mean particle speed correlation. The motion of the particles within a fluidized bed is studied by following the motion of a tracer particle. In order to visualize the movement of a tracer particle and measure its velocity, different experimental techniques were employed. Volpicelli et al. [3] studied particle movement in a monolayer fluidized bed. Handley et al. [4] observed and measured the motion of a tracer particle in a liquid fluidized bed by taking photographs of a transparent bed with an opaque tracer particle (the photographs were taken at various frequencies, ranging from eight per second to one per minute). They used three fluidized bed systems of crushed soda-glass particles of 14–16, 10–12 and 6–8 mesh minimum size, in a bed with a maximum diameter of 76.2 mm. Carlos and Richardson [5] measured individual particle velocities by photographing (about 14 frames per s) the movement of a colored particle in a completely transparent bed of glass particles 9 mm in diameter fluidized with dimethyl phthalate in a glass column of diameter 102 mm. The obtained histograms of the velocity components of the tracer particle followed approximately Maxwell distribution and the histogram of the total particle speed was quite similar to that predicted by the kinetic theory of gases. Latif and Richardson [6] used the same system as [5] but 6 mm particles were fluidized over a much wider range of voidages ($\varepsilon = 0.55$–0.95). They showed that particle speed increased linearly with the superficial liquid velocity. The movement of fluidized particles was anisotropic, with the ratio of the root mean squares of the axial and the radial velocities equal to 2.16. A similar observation was reported by Carlos and Richardson [5] and Hadley [4]. Latif and Richardson [6] also studied the variations of the heat transfer coefficient between a fluidized bed and an electrically heated wire in order to relate the heat transfer coefficients to particle movement. The results they obtained indicated that the maximum value of the heat transfer coefficient occurred in the sections of the fluidized bed in which the particle speed was also maximal. Kmiec [7] investigated the bed structure and particle motion in a glass particles ($d_p = 6.17$ mm)–methyl benzoate fluidized bed. This author found that the mean particle speed was higher at higher fluid velocity and

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that at a low mean liquid velocity, the particle velocities tended to be higher in an upward direction in the center of the bed and in a downward direction at the column wall and that the ratio of the absolute vertical to the absolute horizontal particle velocities was about 2.0 for voidages in the range $\varepsilon = 0.623 - 0.781$. Grbavčić et al. [8] used two-dimensional column 60 × 9 mm to study particle velocities and the velocity distribution by fluidizing spherical glass particles 3.09 mm in diameter. Limtrakul et al. [2] used advanced non-invasive gamma rays-based techniques, computer tomography and computer-aided radioactive particle tracking to measure solid holdup and solid velocity profiles in liquid–solid fluidized beds. Two fluidization columns $D_c = 0.1$ m and $D_c = 0.14$ m were used. The fluid used was water while the solids were spherical glass particles $d_p = 1$ and 3 mm and acetate spheres $d_p = 3$ mm. The time-averaged velocity measurements indicated that multiple circulation cells existed in the column. The solid motion was upward in the center and downward near the walls in the fully developed part of the column. The flow pattern was reversed in the entry region of the column. The solids mean speed increased with increasing liquid superficial velocity, column size, particle size and density. Solids mean axial velocities increase with increasing liquid superficial velocity, column size, particle size and density. The distributor type affects the solids mean speed while the bed height has less effect.

Understanding the motion of solids in liquid fluidized beds is important not only from phenomenological point of view, but also for the study of some important transport characteristics of the bed. Several authors emphasized the role of particle–particle collisions in heat [9] and mass transfer [10] operations, as well as in the removal of deposits from the particles [11], which is particularly important in backwashing of downflow granular filters, especially sand filters. Collisions with the tube walls, which are related to particle–particle collisions, are of great importance in liquid–solid fluidized bed heat exchangers for the removal of deposits on the walls and prevention of fouling [12]. Correlations for predicting the frequency of collisions in particulatively fluidized beds were proposed by Nelson and Skaates [11], Gidaspow [13] and Aghajani et al. [9]. All the proposed correlations require knowledge of mean particle speed. The scope of the present work was to collect a sufficient amount of experimental data for the development of a correlation for the mean particle speed as well as to analyze the velocity and speed distributions in the light of well-known equations developed in the kinetic theory of the gaseous state.

2. Experimental

Experiments were performed using mono-sized spherical glass particles 1.94, 2.98, 4.00 and 6.00 mm in diameter and four two-dimensional columns. For each particle size, a separate column was constructed so that the column thickness corresponded to approximately 3 particle diameters. The height of each column (between the distributor and the overflow) was 400 mm. The geometric characteristics of the columns are summarized in Table 1. The columns were equipped with a distributor, calming section, piezometers and Yamatake–Honeywell electromagnetic flow meters, as shown schematically in Fig. 1. The calming section of the columns was a fixed bed section 150 mm in height, made of spherical particles 2 mm in diameter (for the smallest column) or 3 mm in diameter (for the other three columns). The fluid used in the experiments was deaerated water at a nearly constant temperature of 20 °C ($\rho_f = 1000$ kg/m^3, $\mu = 1.19\ 10^{-3}$ Pas). Bed voidage was determined on a usual way by measuring relationships between bed height and superficial fluid velocity for beds of a known mass of particles. During measurements of particle speeds, for each investigated water flow rate, the bed height was adjusted to $H = 400$ mm. One dark-colored tracer particle, the motion of which was recorded using a video camera with a strong light behind the column, was placed into the bed. The video camera was positioned at 0.7 m from the bed. The first step in the analysis of the video-recordings was the removal of the parts of the recording in which test particle was outside the test section. The test section was the area between $z = 50$ and 270 mm (Fig. 1). The effective duration of the video recording for each run was about 3 min with about 30 strips (segments). The video recording was made using 29.97 frames/s. The next step was projecting the video recording onto paper using a video beam and making the record on the paper of the position of the center of the test particle on successive frames. The obtained picture was scanned and analyzed using SigmaScan [14] image analysis software. The distance and area calibration of the system were performed before analysis of each scan in SigmaScan software. The output file obtained using SigmaScan software contained the particle coordinates, the distance between two successive points (positions of the particle), the slope of the line between two successive points and cumulative distance traveled by the test particle. The data were used to calculate the total particle speed, as well as the axial and horizontal components of the particle velocity vector. Since the column thickness was approximately 3 × particle diameters, only the motion of the tracer particle in the z–x-plane was studied.

Table 1
Column characteristics.

d_p mm	D_c mm	b mm	D/d_p	b/d_p
1.94	139.0	6.0	71.6	3.1
2.98	138.0	10.0	46.3	3.4
4.00	185.0	13.0	46.3	3.3
6.00	278.0	20.4	46.3	3.4

3. Results and discussion

3.1. Fluidization parameters

Bed behavior was characterized as particulate, although by visual observation the voidage distribution is not uniform. Regions of higher and lower particle concentration, i.e. liquid voids, instantaneously appear and disappear, although overall expansion is regular i.e. the relationship $U(\varepsilon)$ is monotonically increasing function. Frequency of liquid

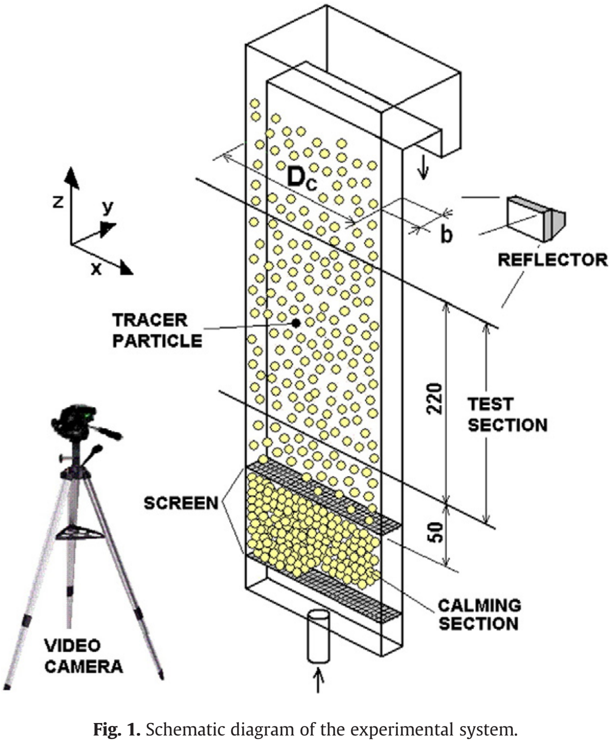

Fig. 1. Schematic diagram of the experimental system.