Particle Dynamics Near the Surface of a Horizontal Tube in a Gas-Fluidized Bed

R. Vadivel and S. C. Saxena
Department of Chemical Engineering
University of Illinois
Chicago, IL 60680

The knowledge of particle concentration, their velocities and residence times at an immersed surface in a gas-fluidized bed is essential for proper reactor design. The voidage distribution is needed to validate any mechanistic theory for heat transfer (Ganzha et al., 1982). Kimura et al. (1955) and Denloye and Botterill (1978) contend that the voidage at the tube surface, ϵ_s, is larger than its value in the bulk of the bed, ϵ_b, and further this voidage variation is limited for a packed bed to a region of about half a particle diameter from the surface. Recently renewed interest has arisen in understanding the particle dynamics near the tube surface due to its implication in explaining and understanding the phenomenon of boiler tube erosion in fluidized-bed combustors (Stringer and Wright, 1986).

This led Saxena et al. (1987) to develop an image carrying fiber optic probe technique to investigate the variation of ϵ_s around the periphery of a horizontal tube as a function of superficial fluidizing velocity, U. However, this study was confined to only values of U smaller than 1.10 U_{mf}. Here U_{mf} is the value of the superficial minimum fluidization velocity. This restriction was due to the use of low speed (30 frames per second) TV camera and video cassette recording system. In the work reported here a high speed Kodak EktaPro 1000 motion analysis equipment is used and consequently ϵ_s and particle dynamics is investigated over a much wider velocity range. However, the instrument was available only for a very limited time; therefore, the measurements completed and results obtained are relatively restrictive in scope. Nevertheless, these illustrate the powerful potential and promise of this novel technique in reactor design and diagnosis in general.

Experimental Equipment

The fluidized-bed experimental facility used in the present series of experiments is described by Verma and Saxena (1983). Here, only the modifications made to adopt it for this work are described. The square fluidized-bed column which is 0.305 m to a size is reduced to 0.153 m by inserting solid wooden blocks in the test bed section as well as in the plenum chamber. The air distributor plate is also accordingly changed but the bubble caps are of the same size and design as used in the earlier work. The hydrodynamic behavior of this modified fluidized bed is the same as that of the original bed in the earlier work of Saxena et al. (1987). This is confirmed by conducting bed to tube heat transfer measurements for an identical tube and bed material in the two cases as a function of fluidizing velocity.

In the present investigations, spherical glass beads of a narrow size range (1.2 to 1.7 mm) with an average diameter of 1.4 mm are used. The heat transfer tube is simulated by a glass tube 50.8 mm in diameter, installed horizontally in the bed test section at a height of 28.0 cm above the distributor plate. The image carrying fiber optic probe, hereafter referred to as the borescope, the external light source and the C-mount lens used are the same as in the earlier work of Saxena et al. (1987). Kodak EktaPro 1000 motion analysis system is used for photographing, monitoring and recording the particle motion at the tube surface at two angular positions for a range of fluidizing velocities.

The Kodak system, which is still in the state of development, consists of a processor with keypad, imager with electronic viewfinder, and a video monitor. It records at frame rates of 30, 60, 125, 250, 500 and 1,000 full frames per second. The recording speed can be upgraded up to 6,000 pictures per second by split frame formats of 1, 2, 3, 4 or 6 pictures per frame. It has normal playback capability and can display one frame at a time forward or reverse at a slow continuous rate in the jog mode. The imager (camera) with electronic view finder and C-mount with electronic remote control capability for zoom, focus and exposure uses a 18-108 mm zoom lens and a maximum aperture of f/1.8. It has control keys for live, record and stop operations. As hardcopy printer, Mitsubishi video copy processor model P60U is used. The particle motion recorded at a higher frame rate is transferred on a high-density Scotch color-plus video cassette at the standard rate of 30 frames per second. This tape is finally analyzed on an industrial Panasonic video cassette recorder which has four video heads, two are used for normal playback and the other two are used for slow and still modes of operation, in conjunction with a black and white TV monitor.

Spatial measurements are taken with the help of cross hair which are activated electronically and can be moved to any position within the frame area. X and Y coordinates data in digital form are displayed alongside the frame to indicate cross-hair position. Frame number and elapsed time are also displayed in digital form so that time-displacement information such as speed and acceleration can be determined within minutes of recording an event. The details of the test runs, and their operating and recording conditions are given in the next section.

Experimental Results

The borescope is inserted inside the horizontal glass tube and is used to view the downstream side or top end and the lateral right side of the tube. These two positions are referred to as 0° and 90° positions of the tube respectively. The minimum fluidization velocity of the glass beads is 79.5 cm/s, and measurements conducted here are up to the superficial gas velocities of 2 U_{mf}. The borescope views a test area of 4.0 × 5.5 mm in a horizontal plane at 0° position and in a vertical plane at 90° position. The particle movement is recorded at the rate of 125 and 250 frames per second at the 0° position, and at the rate of 500 frames per second at the 90° position. In our discussion of particle concentration at the tube surface and surface voidage calculation, we consider only a region around the tube enclosed by the first layer of solid particles in conformity with our earlier work. Further, ϵ_s calculations consider a cylindrical test volume bounded by the viewed test area and a height equal to particle radius. Thus, if all the particles in the test section are farther than 0.5 d_p from the tube surface, the surface voidage by definition will be unity. The details of these calculations are given in Saxena et al. (1987). Briefly, ϵ_s is defined as:

$$\epsilon_s = 1 - F\frac{\text{Total Area of Particle Images on Screen}}{\text{Total Area of TV Screen}}$$

Here, F is defined as the ratio of volume of the spherical particle enclosed within a distance of particle radius form the tube surface to the volume of the cylindrical test section of diameter equal to the particle diameter and height equal to particle radius. The image size of a particle and hence the magnification factors depends on the particle position relative to the tube surface. Experimentally the magnification factors are determined for particles of known diameters and located at different known position above the tube surface. The correction factor is then determined by interpreting the magnification factor from the average area of the particles on the TV screen.

At the 0° position, the particle movement is recorded at five different air fluidizing velocities (U/U_{mf} = 1.1, 1.3, 1.5, 1.7 and 2.0) in a horizontal X-Y plane. These data are then used to obtain the particle trajectories giving the particle position as a function of time at each of the five air velocities. These trajectories are used to obtain particle speed as a function of gas velocity and the same are reported in Figure 1 as average particle speed versus U/U_{mf}. Similar data are taken for the 90° position and the final computed average particle speeds for different gas velocities are also shown in Figure 1.

Certain interesting observations are evident from Figure 1. The particle speeds at the 0° position are almost an order of magnitude smaller than the 90° position. At both the positions the particle speed is dependent on the fluidizing gas velocity. It appears that the particle motion is a monotonic increasing funciton of gas velocity. At the 0° position, the particle motion is feeble for gas velocities up to about 1.5 U_{mf}, and perhaps becomes relatively pronounced for gas velocities above about 2 U_{mf}. At the 90° position the particle motion seems to be relatively feeble for gas velocities smaller than about 1.3 U_{mf} but it steeply increases as the gas velocity is increased. For gas velocities greater than about 1.5 U_{mf} the particle speed seems to be a weaker function of gas velocity. However, the particle speeds are about an order of magnitude greater in the latter velocity range than the values in the former range.

Based on our earlier measurements of bubble velocity in a somewhat comparable gas-solid system (Mathur et al., 1987), we find that the particle speeds are about 0.6 times the bubble velocity. This calculation is approximate because the bubble

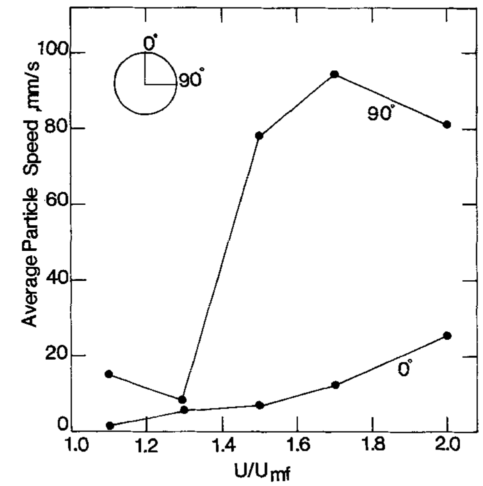

Figure 1. Average particle speed as a function of *U* at 0° and 90° positions on the tube surface.

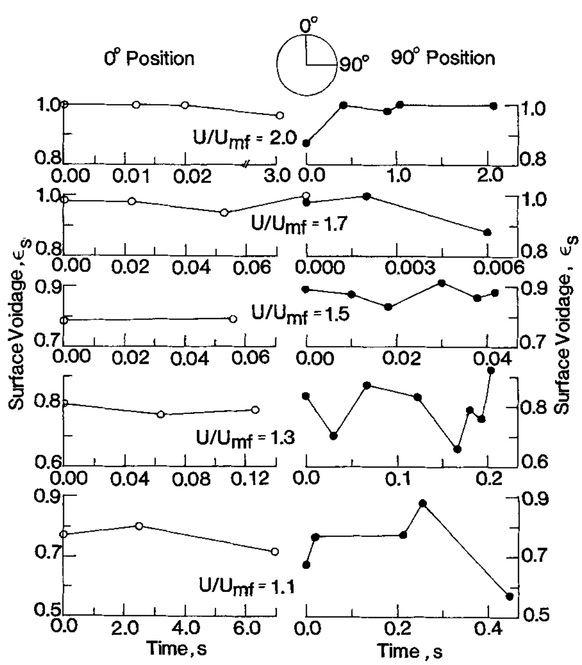

Figure 2. Variation of surface voidage with time.

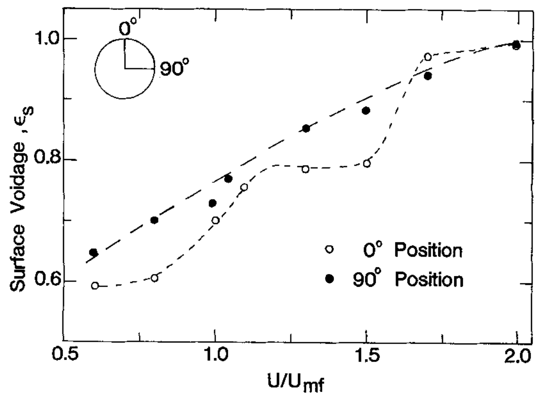

Figure 3. Variation of time averaged ϵ_s values with U/U_{mf}.

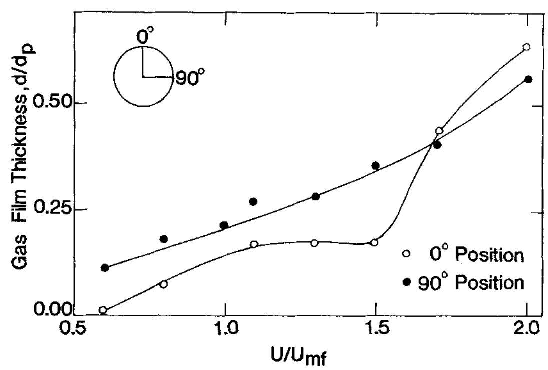

Figure 4. Variation of time averaged gas film thickness with U/U_{mf}.

velocity is dependent on bubble size and the measurements of Mathur et al. (1987) are made in an unbaffled two-dimensional fluidized bed. Further, the wall effect will tend to reduce the measured bubble velocity in a two-dimensional bed. Thus, qualitatively the value 0.6 may constitute the lower limit for this number.

These results also suggest that the tube wear of the boiler tubes in a fluidized-bed combustor is likely to be much more serious at the 90° position as compared to that at the 0° position.

Computed values of the surface voidage with time at various air velocities for the two positions at the tube surface are shown in Figure 2 as obtained from a typical run. It has a direct relationship with the bubble frequency at the tube surface. However, in our measurements this latter property is not measured. Time averaged ϵ_s values are displayed in Figure 3. At the 0° position the ϵ_s values are smaller than that at the 90° position, except at higher gas velocities when these approach each other. Average gas film thickness values between the particles and the tube surface are reported in Figure 4. At the 90° position, the gas film is thicker (roughly 0.25 d_p) than at 0° position (roughly 0.16 d_p), and the two values approach each other at higher gas velocities and exceed 0.5 d_p. All these results are in good agreement with the qualitative results of Decker and Glicksman (1986), who have measured ϵ_s using capacitance surface voidage sensors. The experimental technique proposed here measures appropriately the particle trajectories only as induced by bubble motion. The latter cannot be followed as the test section being viewed is relatively smaller.

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Notation

d_p = average particle diameter
F = correction factor
U = superficial gas fluidization velocity
U_{mf} = superficial minimum gas fluidization velocity

Greek letters

ϵ_b = bulk bed voidage
ϵ_s = surface voidage

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