Particle Contact Dynamics on Tubes in the Freeboard Region of Fluidized Beds

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Gas-fluidized beds are operated with a wide particle size range, and the entrainment of particles into the freeboard region above the dense bed is of practical importance. For example, heat transfer coefficients in the freeboard region are a strong function of void fraction and solid holdup. As a result the heat transfer coefficient is reduced an order of magnitude in the freeboard region as compared to in-bed values (Biyikli et al., 1983). The objective of this investigation was to determine the local and average void fractions that may be experienced by a heat transfer tube located in the freeboard region of gas-fluidized beds.

Experimental Results

An atmospheric fluidized bed, 0.20 × 0.30 × 3.0 m, was used for the experiments (Biyikli et al., 1983). Local void fractions resulting from transient particle contacts on a 29 mm horizontal tube were determined by the capacitance probe technique of Ozkaynak and Chen (1978). The probe output was continuously monitored on a digital oscilloscope to obtain dynamic records of the time-varying void fractions. Local void fractions were measured around the circumference of the horizontally placed tube with air velocities of 0.25 to 3.0 m/s.

A sample probe signal for a given gas flow rate for 19 cm tube elevation is shown in Figure 1. The signal indicated a distinct periodic variation of void fractions between a dilute void phase (lean phase) and packed particles (dense phase). Statistical analysis of the transient void fractions indicated a bimodal probability distribution, with peaks at void fractions of 0.6 and 0.9.

Local void fractions around the tube were calculated as the time-averaged values over 4 s intervals. Several measurements of such values were obtained for each angular position around the tube. Deviations of these time-averaged samples were within ±7% of the mean value. The area-averaged value of local void fractions at the top, bottom, and sides of the tube was then taken as the tube-average void fraction for that elevation.

For a selected static bed height of 36 cm, the instrumented tube was placed at 1.6, 19, 58, 147, and 225 cm elevations. Tube elevation is defined as the height between the static bed upper surface and the centerline of the test tube. Data were obtained for glass spheres with mean diameters of 275 and 850 μm, and silica sand with mean diameter of 465 μm.

The variation of average void fraction for silica sand along the freeboard height is shown in Figure 2. It is seen that average void fractions are in the range of 0.65 to 0.85 at lower elevations, increasing with increasing elevation and asymptotically approaching unity at high elevations. The parametric effect of fluidization velocity is also shown in the figure. As anticipated, increasing velocity causes particles to be entrained to higher freeboard elevations.

Also shown in Figure 2 is a comparison of the present data with some limited data from prior investigations. It should be noted that the earlier measurements were obtained in the bulk freeboard space while the present measurements were obtained on the surface of a horizontal tube located in the freeboard. In spite of the difference in specific parameters, a general agreement in trends is observed.

Based on these experimental results, an attempt was made to define a limiting entrainment height. This is considered to be the freeboard elevation above which the average void fraction is so close to unity that entrainment of particles out of the bed is negligible, i.e., the effect of particle presence on the process (heat transfer, combustion, etc.) is negligible. For this study, this limiting entrainment height H_L is defined as the freeboard elevation above the static bed for which the average void fraction around the probe tube reaches a value of 0.98 for a given gas velocity.

The need to define such a limiting entrainment height is partly due to lack of definite knowledge of the transport disengaging height (TDH). Zens and Weil (1985) gave a simple graphical correlation of TDH. The correlation is based pri-

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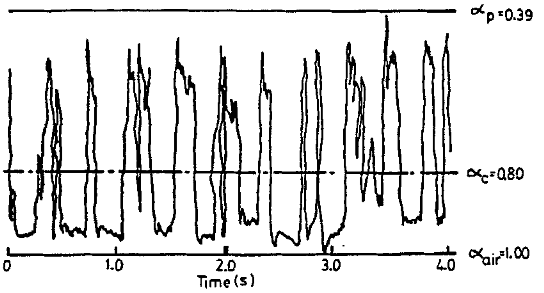

Figure 1. Typical probe signal at top of tube.
275 μm glass beads; tube elevation, 19 cm.; flow rate, min. fluidization velocity ×20

marily on fluid-cracking catalyst particles and tends to be conservative (high TDH) when applied to larger particles. Fournol et al. (1973) also studied fluid-cracking catalyst and obtained a simple correlation for TDH. However, their superficial gas velocities ranged only between 0.11 and 0.22 m/s, and extrapolation leads to excessively conservative values. Hence, there appears to be no reliable correlation to predict TDH.

The limiting entrainment height as defined here was obtained from data such as those represented in Figure 2. The results for different test particles are plotted in Figure 3 as a function of excess superficial gas velocity (velocity above minimum fluidization). As can be seen, the limiting entrainment height is a strong function of gas velocity and particle diameter, increasing with increasing gas velocity and with decreasing particle diameter. Figure 3 also shows the limiting entrainment heights calculated from Ismail and Chen's (1984) data for 475 m dia. silica sand. The agreement is satisfactory for the entire range of gas velocities.

Entrainment is strongly dependent on many system variables, as stated by Matsen (1979). Typically, entrainment may increase with increasing gas velocity and gas density and may decrease with increasing particle size and particle density. Furthermore, it would be expected that entrainment would increase with increasing gas viscosity. Considering these parametric effects, a general nondimensional correlation of the following form is suggested here for the limiting entrainment height:

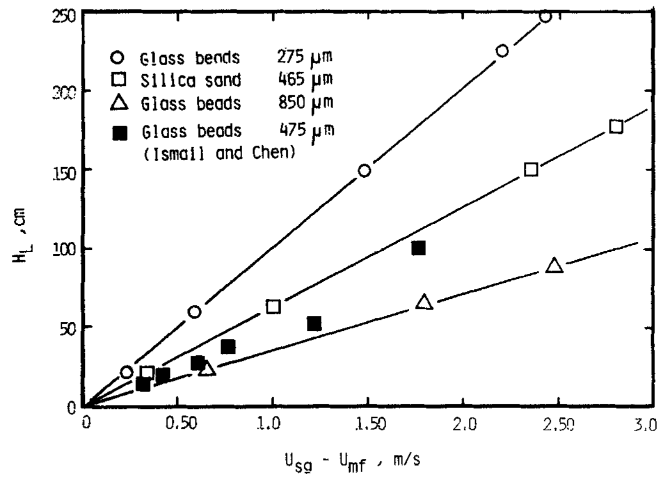

Figure 3. Limiting entrainment height for various test particles.

$$\frac{H_L}{d_p} = c_1 \left[\frac{(U_{sg} - U_{mf}) \rho_g \mu_g}{d_p^2 (\rho_s - \rho_g)^2 g} \right]^{c_2}$$

where c_1 and c_2 are constants to be determined from the experimental data. By a least-squares fit to the data of Figure 3, the constants c_1 and c_2 were found to be 8.32×10^8 and 1.0, respectively. The agreement of the data with the resulting correlation is shown in Figure 4; the average deviation is 6%.

Summary

Particle contact dynamics on horizontal tubes in the freeboard region of fluidized beds were measured and analyzed to obtain local void fractions around a tube. Local void fractions indicated a distinct periodic variation between a dilute void phase and a densely packed phase. Average void fractions increased with increasing freeboard elevation and decreased with increasing velocity and with decreasing particle diameter. A limiting entrainment height was defined and correlated in terms of operating conditions, which should be useful in design models.

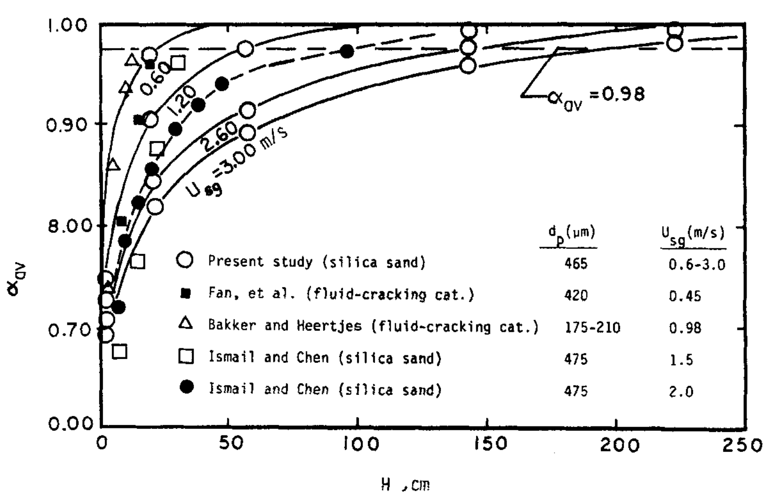

Figure 2. Variation of average void faction along freeboard height.
Silica sand, 465 μm mean dia.

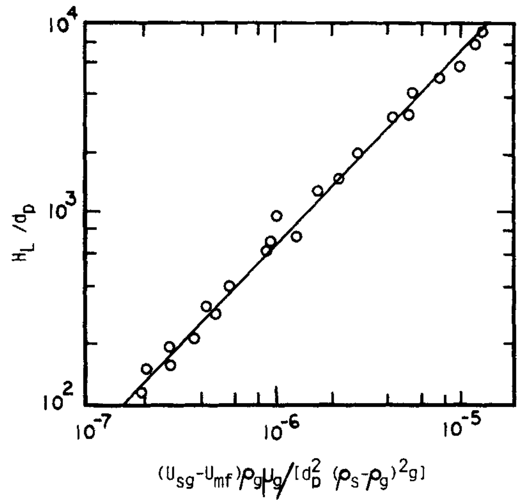

Figure 4. Comparison of experimental data with limiting entrainment height correlation.

Acknowledgment

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Notation

d_p = mean particle diameter, m
g = acceleration of gravity, m/s^2
H = freeboard elevation, m
H_L = limiting entrainment height, m
U_{sg} = superficial gas velocity, m/s
U_{mf} = minimum fluidization velocity, m/s

Greek letters

α = void fraction
α_{av} = average void fraction around tube
α_p = void fraction of packed bed
ρ_g = density of air, kg/m^3
ρ_s = density of particles, kg/m^3
μ_g = viscosity of air, kg/m.s

Literature cited

Bakker, P. J., and P. M. Heertjes, "Porosity Measurements in a Fluidized Bed," *Brit. Chem. Eng.*, **3**, 240 (1958).

Biyikli, S., K. Tuzla, and J. C. Chen, "Heat Transfer Around a Horizontal Tube in Freeboard Region of Fluidized Beds," *AIChE J.*, **29**(5), 712 (1983).

Fan, L. T., C. J. Lee, and R. C. Bailie, "Axial Solid Distribution in Gas-Solid Fluidized Beds," *AIChE J.*, **8**(2), 239 (1962).

Fournol, A. B., M. A. Bergougnou, and G. G. J. Baker, "Solids Entrainment in a Large Gas-Fluidized Bed," *Can. J. Chem. Eng.*, **51**, 401 (1973).

Ismail, S., and J. C. Chen, "Volume Fraction of Solids in the Freeboard Region of Fluidized Beds," *AIChE Symp. Ser.* 234, **80**, 114 (1984).

Matsen, J. M., "Entrainment Research: Achievements and Opportunities," NSF Workshop Fluidization, Fluid Particle Systems, Rensselaer Polytec. Inst., 452 (1979).

Ozkaynak, T. F., and J. C. Chen, "Average Residence Times of Emulsion and Void Phases at the Surface of Heat Transfer Tubes in Fluidized Beds," *AIChE Symp. Ser.*, **74**, 334 (1978).

Zenz, F. A., and N. A. Weil, "A Theoretical Empirical Approach to Mechanism of Particle Entrainment from Fluidized Beds," *AIChE J.*, **4**(4), 472 (1958).

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