Effect of Column Inclination on the Performance of Three-Phase Fluidized Beds

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Inclining a fluidized bed column by as little as 1.5 degrees greatly affects the bed characteristics. The bed contracts, the particle-liquid mass-transfer and heat-transfer coefficients increase by up to 30%, and the gas-liquid mass-transfer coefficient can either be increased by up to 15% or decreased by up to 20%.

Introduction

In bubble columns, a small column inclination from the vertical leads to smaller gas holdups (Yamashita, 1985). In addition, an inclination of less than 0.5 degree can increase the axial dispersion coefficient by 2 orders of magnitude (Rice et al., 1987).

The effect of column inclination on three-phase fluidized beds has never been studied, to our knowledge. Moreover, previous studies of three-phase fluidized beds have not apparently, accurately controlled the column inclination.

From a practical point of view, column inclination may have detrimental or beneficial effects on the performance of fluidized beds. From a more academic point of view, apparent disagreements between the results of various academic studies (Fan, 1989) may be due to minor and different deviations from column verticality.

The objective of this article is, thus, to show how column verticality affects hydrodynamics, gas-liquid mass transfer and particle-liquid heat and mass transfer under conditions typical of past academic studies of three-phase fluidized beds, that is, 3 mm glass beads as particles, water as liquid, air as gas and a column diameter of 8 cm (Dhanukha and Stepanek, 1980; Nguyen-Tien et al., 1985; Fukuma et al., 1988; Nikov and Delmas, 1987). The selected column inclination was such that it could not be detected visually; it was, thus, representative of the column inclinations which may have been present in past studies.

Experimental

The inside diameter of the fluidized bed column was 0.08 m. For the experiments with the vertical column, the verticality was first established by fluidizing the bed and checking the bed behavior though the Plexiglas wall. The verticality was, then, confirmed by checking for the absence of any radial profile of the particle-liquid heat-transfer coefficient. For the experiments with an inclined column, the inclination was measured with a plumb line and was found to be between 1.4 and 1.8 degrees. The fluidized particles were 3 mm spherical glass beads with a density of 2,471 kg/m^3. Their minimum fluidization velocity was 0.032 m/s. The mass of particles introduced in the column was kept constant at 2.44 kg, giving fluidized bed heights of around 0.4 m.

The liquid, a 5 wt. % aqueous solution of sodium chloride, was pumped from a tank where a heat exchanger kept the liquid at 25 ± 0.2°C. The gas was air, except for the gas-liquid mass-transfer measurements for which bottled nitrogen was used. For the heat-transfer measurements, the air was first saturated with water vapor in a packed bed humidifier. The phase holdups were determined from the vertical pressure profile.

The particle-liquid mass-transfer coefficient was measured with the standard electrochemical technique. Dissolved oxygen was reduced at the surface of 5 mm fixed silver spheres. The particle-liquid mass-transfer coefficients were obtained from an average of 25 to 30 local values obtained at 5 or 6 different heights and 5 different radial positions for each height. The radially averaged coefficient did not significantly vary with height. Del Pozo et al. (1991a) showed that fixed spheres such as used in this study gave, in practice, the same results as tethered spheres which themselves gave the same results as completely free spheres, provided the tether was long enough (Prakash et al., 1984). Details are provided by Del Pozo et al. (1991a,b).

The particle-liquid heat-transfer coefficient was measured with self-heated thermistor probes. Each probe, which was about 3 mm in diameter, was fixed at the tip of a horizontal stainless steel tube. Although no experiments could be conducted to check that the heat-transfer coefficient was the same for fixed probes and free-floating particles, they should be similar since the mass-transfer coefficient was the same for these two types of particles. Details are provided by Del Pozo et al. (1991a,b). The particle-liquid heat-transfer coefficient was measured, for the inclined column, at 5 radial positions.

Gas-liquid mass transfer was measured with an improved "pseudo steady-state" physical desorption technique. The column was, first, operated normally with air as fluidization gas. Nitrogen was then substituted for the air. The 6 spherical electrodes which were used for the particle-liquid mass transfer were used to monitor the resulting changes in dissolved oxygen concentration at 6 heights. When the column was vertical, the radial variations of the dissolved oxygen concentration were negligible and the electrodes were kept on the column axis. When the column was inclined, the desorption experiment was repeated 5 times with different radial positions to obtain accurate radially averaged oxygen concentrations.

Experimental Results

Phase holdups

The column inclination did not seem to lead to defluidized zones. This was established, in presence and absence of gas, by visual observations. It was confirmed, in the absence of gas, by checking, from the pressure measurements, that the whole weight of particles was supported by the liquid. It was also confirmed, in the presence of gas, by checking that the measured pressure gradient near the grid was the same as in the rest of the bed.

The column inclination reduced the bed height and increased the solid holdup by 5 to 8% as shown in Figure 1. This increase was not greatly affected by the liquid or gas velocities. On the other hand, the column inclination reduced the gas holdup by 25 to 50% (Figure 2). The gas bubbles concentrated near the higher side of the column (due to the inclination, one side was higher than the other) where they formed wall slugs which moved rapidly along the wall. The cylindrical shape of the column, however, restricted visual observations to the wall regions.

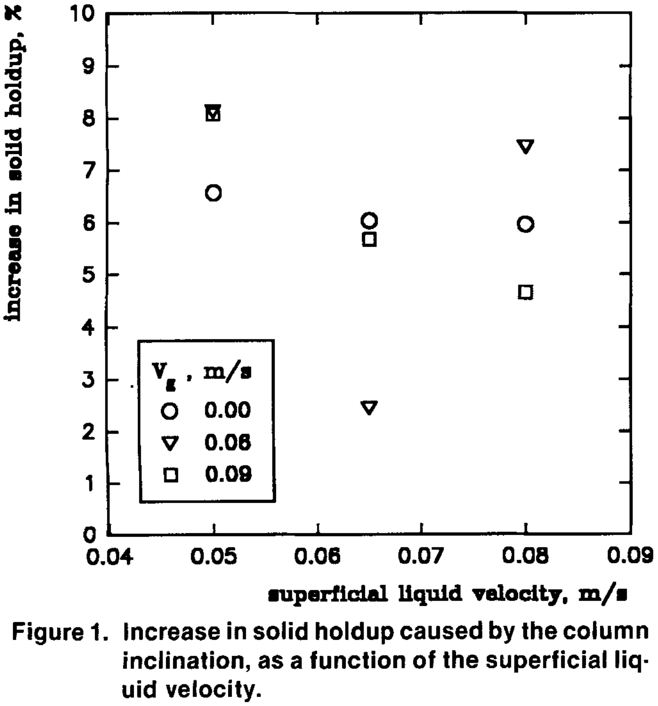

Figure 1. Increase in solid holdup caused by the column inclination, as a function of the superficial liquid velocity.

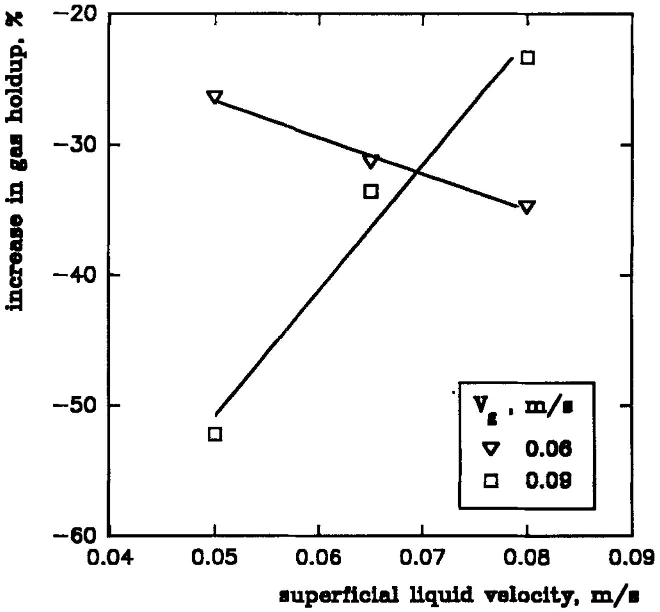

Figure 2. Increase in gas holdup caused by the column inclination, as a function of the superficial liquid velocity.

Relative changes in bubble size, throughout the whole bed, were roughly estimated from relative changes in bubble slip velocity. In a three-phase fluidized bed, each gas bubble rises through a mixture of liquid and gas bubbles which flows between the particles. The velocity of this mixture must be evaluated to obtain the bubble slip velocity. The gas-liquid mixture occupies a fraction ($\epsilon_g + \epsilon_L$) of the column volume and has a total superficial velocity of ($V_g + V_L$). Its actual velocity, relative to the column wall, is, therefore:

$$U_{\text{mix}} = (V_g + V_L)/(\epsilon_g + \epsilon_L) \tag{1}$$

The slip velocity of the gas bubbles, relative to this gas-liquid mixture, is thus given by:

$$U_{B\text{slip}} = (V_g/\epsilon_g) - U_{\text{mix}} = (V_g/\epsilon_g) - (V_g + V_L)/(\epsilon_g + \epsilon_L)$$
$$= U_{GL}/\epsilon_g \tag{2}$$

where U_{GL} is the "drift flux" which was successfully used to model three-phase fluidized beds (Bajpai et al., 1990; Saberian-Broudjenni, 1984).

Figure 3 shows that the column inclination greatly increased the bubble slip velocity. The bubbles were, thus, much larger throughout the bed. This confirms the visual observations.

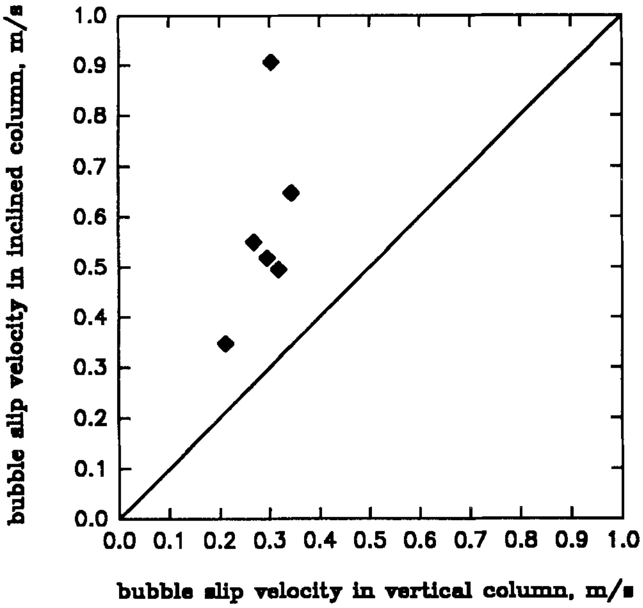

Figure 3. Effect of column inclination on the bubble slip velocity.

Particle-liquid heat transfer

With the vertical column, no significant radial variation of the particle-liquid heat-transfer coefficient could be detected. Column inclination induced large radial variations (Figure 4). In the absence of gas, the particle-liquid heat-transfer coefficient was higher in the higher half of the column (which corresponds to the positive values of r/R). Visual observations indicated that the liquid velocity was much higher near the higher wall of the column. Since increasing the liquid velocity increases the heat-transfer coefficient, the radial variations of the liquid velocity could explain the radial variations of the heat-transfer coefficient.

In the presence of gas, the radial position corresponding to the maximum heat-transfer coefficient was shifted from the wall towards the center (Figure 4). Visual observations indicated that the gas concentrated along the higher wall, displacing the liquid towards the center of column. Since the heat-transfer coefficient is primarily affected by the liquid velocity, its maximum was also shifted towards the center.

Figure 4 shows that, when the column was inclined, the heat-transfer coefficient was higher in the higher side of the column (that is, for $r > 0$) than in its lower side (that is, $r < 0$). This asymmetry was characterized by the "asymmetry coefficient" A_h:

$$A_h = 100^* \ (h_{r>0} - h_{r<0}) / \ [0.5 \ (h_{r>0} + h_{r<0})] \qquad (3)$$

While the radial profiles were perfectly symmetric for the vertical column, inclining the column resulted in large asymmetry coefficients, as shown in Figure 5. The largest asymmetry coefficients were obtained in the absence of gas. Gas flow, by displacing the liquid flow from the higher wall region, reduced the asymmetry coefficient (Figure 5).

The column inclination increased the average heat-transfer coefficient. This increase became larger as the liquid velocity was increased, reaching 25% in presence of gas (Figure 6). In the absence of gas, this increase was lower (Figure 6). This increase was, thus, not solely caused by the radial variations which were more pronounced in the absence of gas (Figures 4 and 5).

One factor which may explain the increase in average heat-transfer coefficient is the bed contraction which was caused by the column inclination (Figure 1). As the bed contracted, it tortuosity increased and the actual liquid velocity past the particle surface became higher.

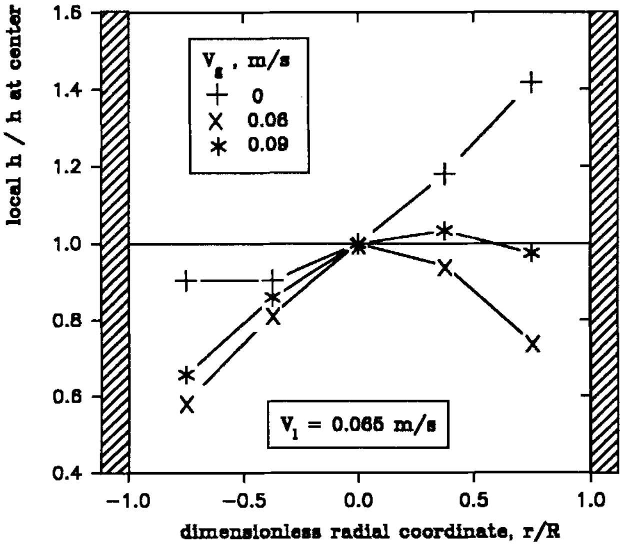

Figure 4. Radial profile of the particle-liquid heat-transfer coefficient ($r/R > 0$ corresponds to the side of the column which is made higher by the column inclination).

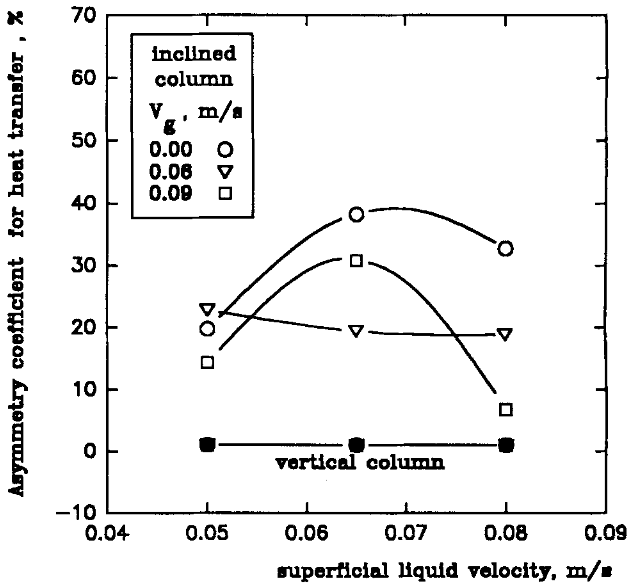

Figure 5. Effect of the liquid and gas velocity on the asymmetry coefficient for particle-liquid heat transfer.

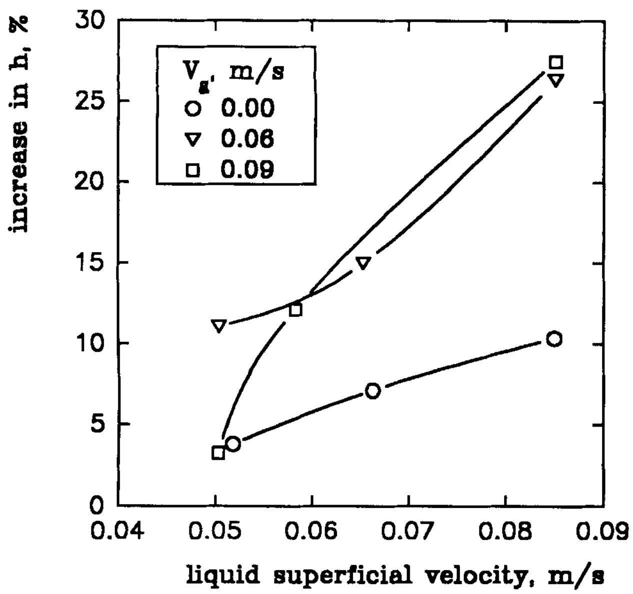

Figure 6. Increase in the bed-averaged particle-liquid heat-transfer coefficient which is caused by the column inclination.

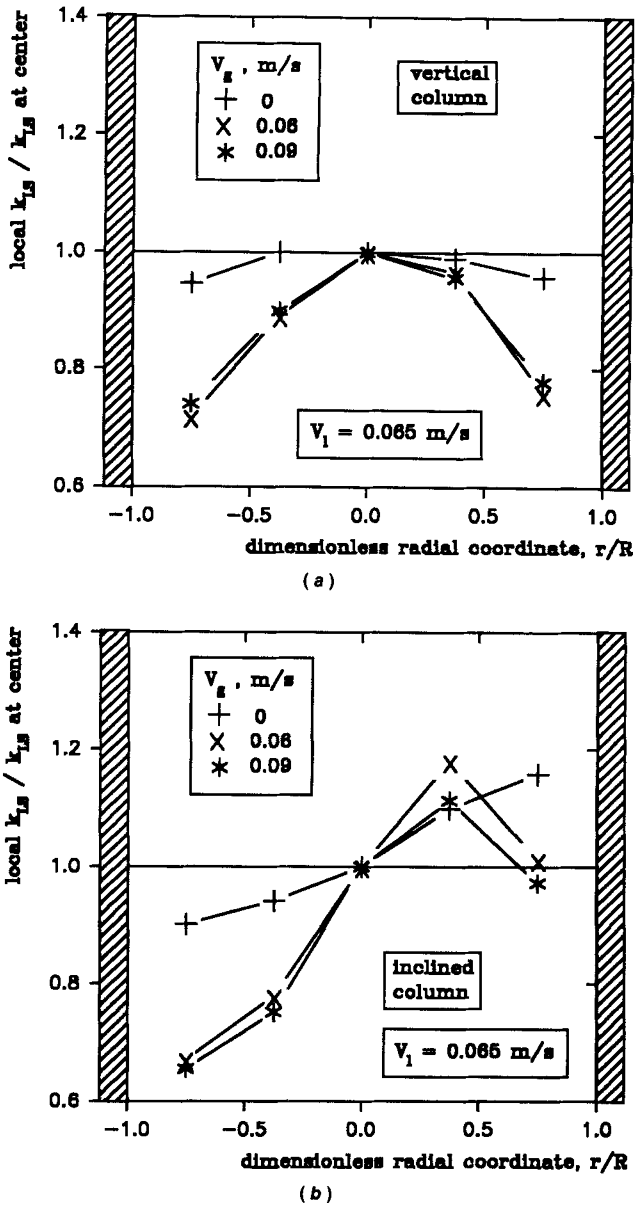

Figure 7. Radial profile of the particle-liquid mass-transfer coefficient.

a. vertical column b. inclined column ($r/R>0$ corresponds to the side of the column which is made higher by the column inclination).

Particle-liquid mass transfer

With the vertical column, the particle-liquid mass-transfer coefficient was maximum near the column axis (Figure 7a). Column inclination displaced the maximum mass-transfer coefficient towards the higher column wall (Figure 7b). In the absence of gas, both the particle-liquid mass-transfer coefficient (Figure 7b) and the heat-transfer coefficient (Figure 4) reached their maximum near the higher wall, presumably because of the higher liquid velocity in this region.

In the presence of gas, the radial position corresponding to the maximum mass-transfer coefficient was shifted from the wall to the center (Figure 7b) but not by as much as for the heat-transfer coefficient (Figure 4). A possible interpretation is that the mass-transfer coefficient is affected not only by the liquid velocity, but also by the gas bubbles which were concentrated near the higher column wall.

Figure 7b shows that, when the column was inclined, the mass-transfer coefficient was higher in the higher side of the column (that is, for $r > 0$) than in its lower side (that is, $r < 0$). This asymmetry was characterized by the "asymmetry coefficient" A_k:

$$A_k = 100^* \ (k_{r>0} - k_{r<0})/[0.5 \ (k_{r>0} + k_{r<0})] \qquad (4)$$

While the radial profiles were perfectly symmetric for the vertical column, inclining the column resulted in large asymmetry coefficients (Figure 8). These results were almost identical to those obtained for heat transfer (Figure 5).

The column inclination increased the average particle-liquid mass-transfer coefficient. This increase became larger as the liquid velocity was increased, reaching nearly 30% in the presence of gas (Figure 9). In the absence of gas, this increase was lower (Figure 9). These increases, as the increases in heat-transfer coefficient (Figure 6), may be caused by the bed contraction which resulted from the column inclination.

Particle-liquid transport

Briens et al. (1992) showed how the film-penetration model is required for accurate predictions of particle-liquid mass transfer under typical industrial conditions. They also showed how the two parameters of this model, the film thickness and the surface renewal frequency, could be obtained by measuring the mass- and heat-transfer coefficients under the same conditions.

In the vertical column, there was a sharp radial profile of the renewal frequency (Figure 10). Visual observations indicated that the bed structure was far from homogeneous and that gas bubbles tended to concentrate at the center of the bed. This confirms that the renewal frequency is sensitive to the

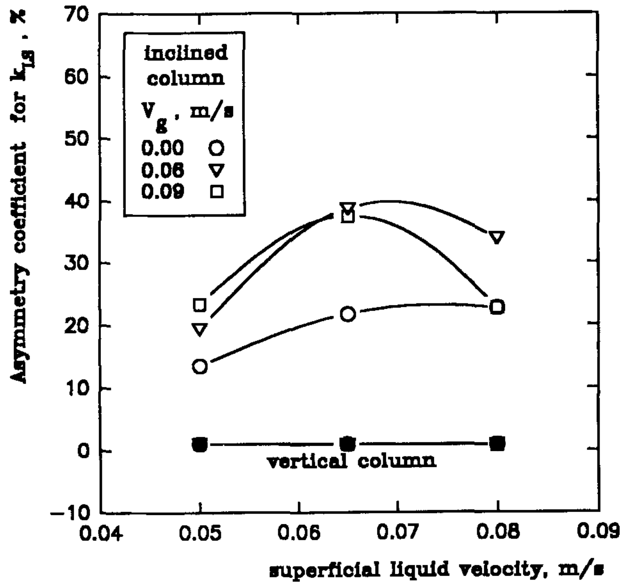

Figure 8. Effect of the liquid and gas velocity on the asymmetry coefficient for particle-liquid mass transfer.

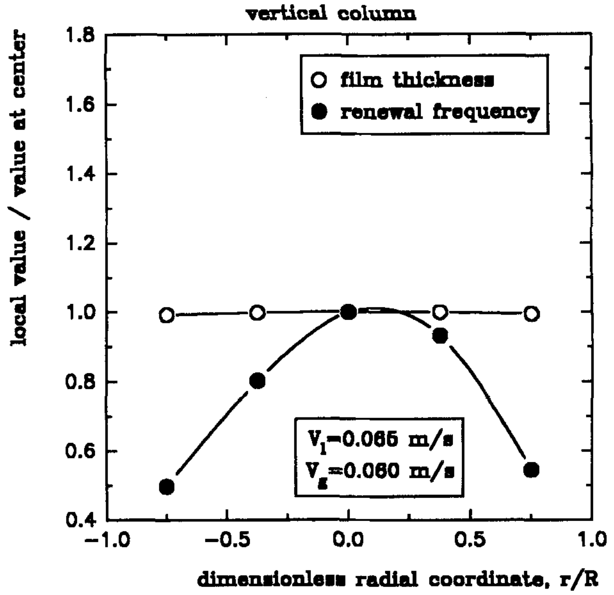

Figure 10. Radial profile of the film thickness, and surface renewal frequency for particle-liquid transport: vertical column.

intermittent flow of the gas bubbles. The film thickness did not exhibit a strong radial profile because it is probably much more sensitive to the average velocity of the continuous phase, that is, the liquid, than to the intermittent gas bubbles (Figure 10).

In the inclined column, the film thickness was smaller in the higher side of the column where the liquid velocity was higher (Figure 11). The minimum liquid thickness, which presumably corresponded to the maximum liquid velocity, was near the column center since the concentration of gas bubbles near the higher column wall displaced the liquid towards the column center (Figure 11). The maximum surface renewal frequency, on the other hand, was moved to a position in-between the center and the higher wall, presumably because the surface renewal frequency is more sensitive to the gas bubbles which were concentrated near the higher wall (Figure 11).

Gas-liquid mass transfer

Getting the gas-liquid mass-transfer coefficient from oxygen desorption experiments required the calculation of the radial average of the dissolved oxygen concentration at each of the

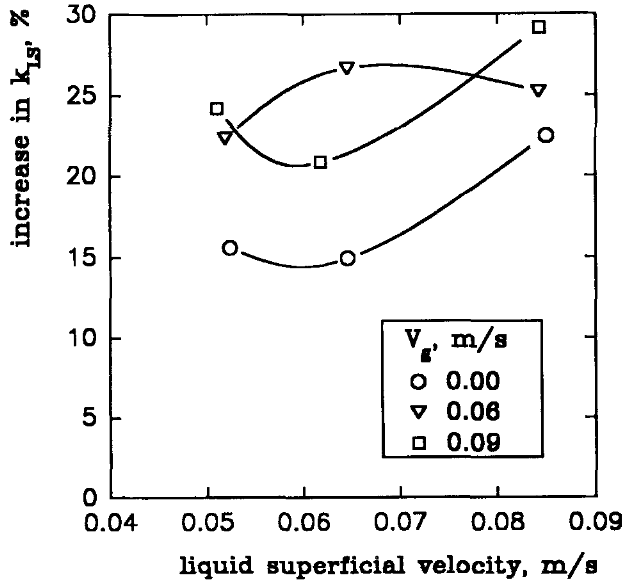

Figure 9. Increase in the bed-averaged particle-liquid mass-transfer coefficient which is caused by the column inclination.

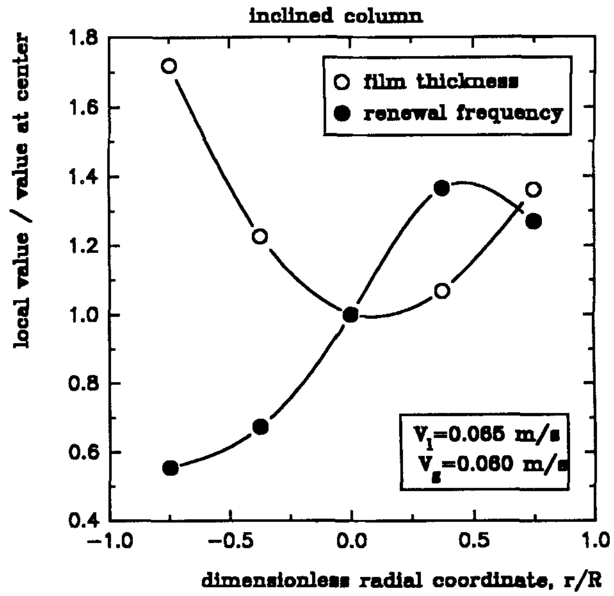

Figure 11. Radial profile of the film thickness, and surface renewal frequency for particle-liquid transport: inclined column.

measurement heights. Two extreme cases were considered. In the first case, no radial variations of the liquid velocity were assumed. In the second case, the radial variations of the heat-transfer coefficient (Figure 4) were assumed to be solely caused by variations in liquid velocity. The liquid velocity was, then, obtained by assuming that the heat-transfer coefficient is proportional to the square root of the liquid velocity, as observed in the absence of particles (Del Pozo, 1991a,b). While the heat-transfer coefficient is primarily affected by the liquid velocity, rather than by the gas bubbles, as shown above, a higher liquid velocity usually results in a larger bed porosity which mitigates the increase of the heat-transfer coefficient. In this second case, the radial variations of the liquid velocity are, thus, overestimated. Taking into account the radial velocity profile did not greatly affect the gas-liquid mass-transfer results.

Although both the plug flow and axial dispersion models gave adequate predictions of the desorption results in the vertical and inclined columns, continuous injections of a colored tracer at various locations showed that neither the plug flow nor the axial dispersion models gave an adequate representation of the complex liquid backmixing patterns. In the inclined column, for example, liquid backmixing was much more intense near the lower column wall. Since the purpose of this study was to compare the mass-transfer performance of the vertical and inclined columns, a gas-liquid mass-transfer efficiency was defined as the ratio of the amount of oxygen desorbed from the liquid in the bed to the maximum amount which could have been desorbed:

$$\eta = (C_{in} - C_{out})/C_{in} \qquad (5)$$

where the concentration C_{out} of the dissolved oxygen in the liquid exiting the bed is obtained by extrapolating the dissolved oxygen concentration profile to the bed surface level. This concentration could be obtained with a good accuracy and the mass-transfer efficiency could, thus, be accurately determined.

Gas-liquid mass transfer was affected by the column inclination (Figure 12). Although, at the lowest liquid and gas velocities, the column inclination increased the gas-liquid mass-transfer rate by 13%, in most cases, column inclination decreased the gas-liquid mass-transfer rate, by as much as 20% for the highest liquid and gas velocities (Figure 12).

Conclusions

Inclining a fluidized bed column by as little as 1.5 degrees greatly affects the bed characteristics. The bed contracts, the particle-liquid mass transfer and heat-transfer coefficients increase by up to 30% and the gas-liquid mass-transfer coefficient can either be increased by up to 15% or decreased by up to 20%.

From an academic standpoint, this means that column verticality must be checked before making any measurements. This has not, apparently, been done in past studies. A relatively easy and very sensitive check of a column verticality would be to measure the radial profile of the particle-liquid heat-transfer coefficient and to ensure that it is perfectly symmetrical.

From a practical point of view, inclining the column may either enhance or degrade the performance of a fluidized bed reactor. The column inclination should, thus, be accurately measured and optimized for each application. The impact of column size on the effects of column inclination has yet to be investigated. Further experiments will be required to establish how the column diameter affects the effects of column inclination.

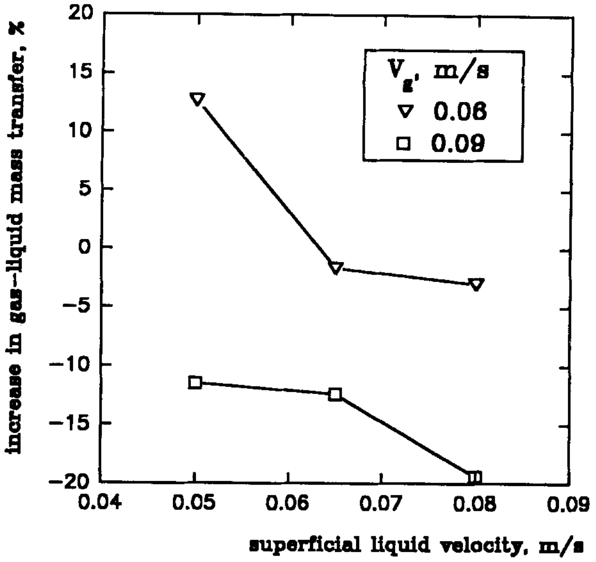

Figure 12. Increase in gas-liquid mass-transfer rate in the fluidized bed caused by the column inclination.

Notation

A_h = asymmetry coefficient for particle-liquid heat transfer (see Eq. 3), %
A_k = asymmetry coefficient for particle-liquid mass transfer (see Eq. 4), %
C_{in} = concentration of dissolved oxygen in the liquid entering the bed, mol/m^3
C_{out} = concentration of dissolved oxygen in the liquid exiting the bed, mol/m^3
C_z = concentration of dissolved oxygen in the liquid at the height z, mol/m^3
D_z = axial dispersion coefficient, m^2/s
h = heat-transfer coefficient, J/(m^2·s·K)
$h, r>0$ = heat-transfer coefficient for the higher side of the column, J/(m^2·s·K)
$h, r<0$ = heat-transfer coefficient for the lower side of the column, J/(m^2·s·K)
H_B = fluidized bed height, m
$k, r>0$ = particle-liquid mass-transfer coefficient for the higher side of the column, m/s
$k, r<0$ = particle-liquid mass-transfer coefficient for the lower side of the column, m/s
k_La = volumetric gas-liquid mass-transfer coefficient, L/s
k_{Ls} = particle-liquid mass-transfer coefficient, m/s
R = column radius, m
r = radial coordinate, that is, distance from the column axis (for the inclined column, $r>0$ corresponds to the column side which is made higher by inclination), m
U_{Bslip} = bubble slip velocity, relative to the gas-liquid mixture, m/s
U_{GL} = drift flux, m/s
U_{mix} = velocity of the gas-liquid mixture, m/s
V_g = superficial gas velocity, m/s
V_L = superficial liquid velocity, m/s
z = height from the grid, m
ϵ_g = gas holdup
ϵ_L = liquid holdup
η = gas-liquid mass-transfer efficiency (see Eq. 5)

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