Mechanism of Particle Entrainment in a Gas-Liquid-Solid Fluidized Bed

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Particle elutriation is an important problem in the practical operation of three-phase fluidized beds and may be significant if the freeboard region is not sufficiently large. The problem appears to be more significant for beds of small and/or light particles than those of large and/or heavy particles. Furthermore, the axial solids holdup distribution differs appreciably between the former and latter types of particles in the freeboard region.

Page and Harrison (1974) studied the fundamental mechanisms for particle entrainment and deentrainment in the transitional region of the freeboard. They indicated that particles are drawn from the upper surface of the fluidized bed into the freeboard in the wake behind a bubble and that vortices containing particles are shed from the wake in the freeboard. They also found that particle entrainment decreased with a decrease in both bubble size and bubble frequency and with an increase in both liquid velocity and particle size. El-Temtamy and Epstein (1980) developed a model to predict solids holdup distribution in the freeboard. In the model, they clearly identified the critical role played by the bubble wake in particle entrainment and by the wake shedding in particle deentrainment. Although the concept of wake transport in multibubble systems is known, quantitative account of the bubble wake behavior in the freeboard is still lacking.

This note provides a quantitative description of fundamental particle entrainment phenomena. It also examines similarities between the single bubble-wake behavior in the in-bed region and that in the freeboard region. The maximum particle-entrainment height attained by a single bubble and successive bubbles is analyzed based on a simple model which takes into account such wake properties as wake shedding frequency and wake velocity.

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Experimental Studies

Experiments were carried out in both two-dimensional (0.8 x 40.6 x 104 cm) and three-dimensional (10 ID x 160 cm) three-phase systems. In the two-dimensional system, the hydrostatic deflection of the column plates was minimized by clamping using three sets of lateral, U-shape Plexiglas channels with square bottoms. Lighting was applied from an oblique frontal angle and/or from the rear. In the three-dimensional system, the column ID was considered to be large enough to yield negligible wall effects on the shape and rise velocity of bubbles of sizes (equivalent diameters) ranging from 0.8 to 2.2 cm in this study. The test section was enclosed in a rectangular viewing vessel made of Plexiglas and filled with tap water to minimize optical distortion. Slit lighting was used to provide a narrow vertical light sheet along the vertical distance traveled by a bubble to obtain a two-dimensional view of the wake flow.

Tap water and nitrogen were used as the liquid and gas phases, respectively. The size and formation frequency of the bubble were controlled electrically through a pulse signal generator and a solenoid valve. All particles used were spherical. Their physical properties are listed in Table 1. All the data analyses, including measurements of the wake properties in the freeboard and the maximum height of particle entrainment, were made via a vertically mobile video camera system. The video camera was capable of moving vertically to track the bubble at any speed up to 60 cm/s.

Results and Discussion

Some physical insights into the mechanisms of particle carryover can be gained by closely following the time evolution of the particle flow around a single bubble. Figure 1 presents a series of photographs reflecting such a time sequence of particle entrainment and deentrainment by a single bubble into the freeboard of a two-dimensional water-774-μm glass-bead fluidized

Table 1. Physical Properties of Particles

Particle	Avg. Dia. mm	Density g/cm^3	Terminal Velocity cm/s	Solids Holdup %	Remarks
Glass (GB774)	0.774	2.50	11.9	41.9	Two-dimensional
Activated carbon (AC778)	0.778	1.509*	5.69	30.8	
Acetate (AT1500)	1.50	1.252	6.99	42.7	
Glass (GB300)	0.300	2.50	4.86	25.5	Three-dimensional
Activated carbon (AC912)	0.912	1.509*	4.83	25	
Acetate (AT1000)	1.0	1.252	4.94	7.6	
Acetate (AT1500)	1.5	1.252	7.4	27.2	
Nylon (NL2500)	2.5	1.15	8.74	25.6	

*Wet density

bed. Figure 1a shows the bubble emerging from the upper free surface of the fluidized bed. A mantle of particles covering the bubble roof drains away and rushes into the near wake of the bubble (Figure 1b). Overall, the particles move upward due to this near-wake capture as well as the drift effect (Darwin, 1953). The latter, however, is confined to the vicinity of the bed surface as characterized by a deformed triangle shape. (See Figure 1c–e.) The particle displacement caused by the drift effect is thus relatively insignificant.

The particles carried by the near wake, on the other hand, may travel further upward in the freeboard. The pressure inside the near wake, whose path closely follows the bubble, is lower than that in the external flow field due to the flow separation at the bubble rim. This pressure defect contributes to entrapment of particles into the near wake, while the instability of the wake flow results in the discharge of some wake material containing particles. As can be seen in Figure 1e–i, the majority of the solids are deentrained via vortex shedding. The entire entrainment-deentrainment process is complete when the solids holdup in the bubble wake becomes negligible.

It is thus important to first examine the wake properties in the freeboard region. The bubble wake in a lower portion of the freeboard was observed to resemble in shape, dimension and stability that in the bed. Figures 2 and 3 show the ratio of the wake length to bubble major axis and the dimensionless bubble rocking frequency (Sr), respectively, in the freeboard near the bed

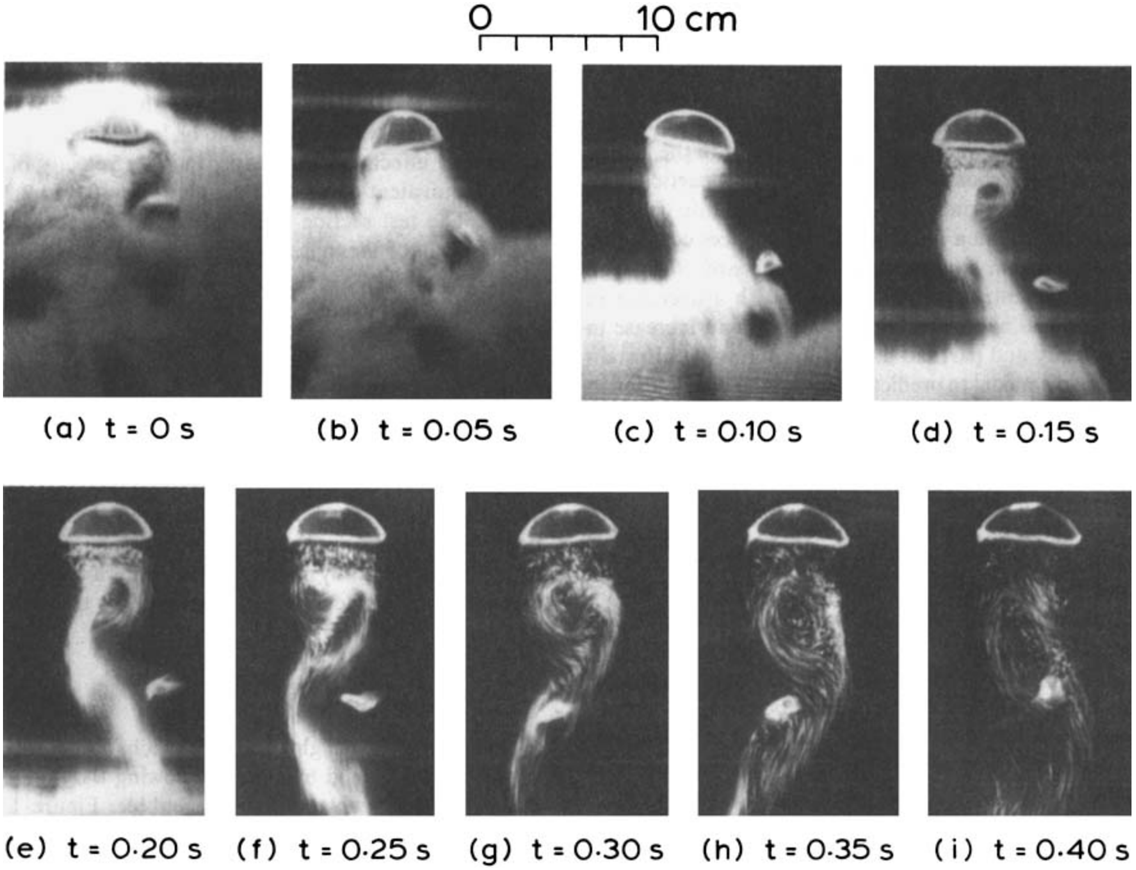

Figure 1. Sequence of particle entrainment and deentrainment by a single bubble into the freeboard of a 2D water-774 μm fluidized bed.

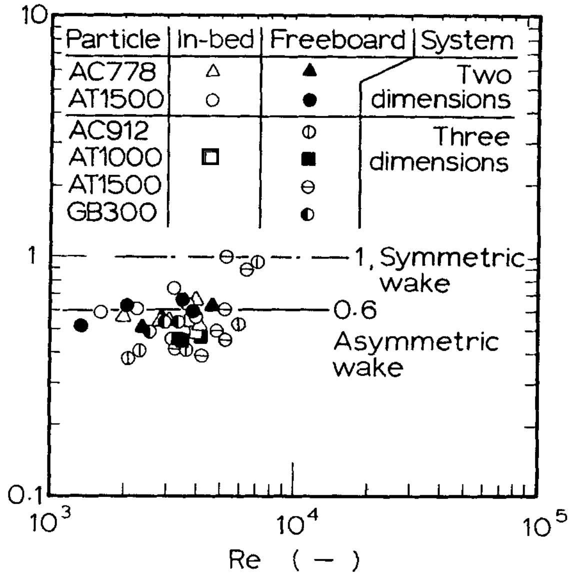

Figure 2. Length of the primary wake of single bubbles in the freeboard near the bed surface.

surface as well as in the in-bed region. It is found that both the wake size and wake shedding frequency, identical to the bubble rocking frequency, in the freeboard at low heights are in the same range as those in the bed regardless of whether the system is two- or three-dimensional. This important finding indicates that using the results of the wake properties for the in-bed enables one to evaluate those for the freeboard and vice versa.

Based on the above discussion, a phenomenological model is developed in this study to quantitatively account for the maximum height of particle entrainment by a single bubble or successive bubbles in the freeboard, H_m. It is noted that experimentally H_m is determined as the height corresponding to a substantial reduction in the amount of particles when the last particle-bearing vortex is shed (Figure 1i), although an insignificant amount of particles may still remain in the wake beyond this height.

Considering that particle entrainment is governed mainly by wake formation and shedding phenomena, H_m can be given as

$$H_m = U_B N_m / f_c \tag{1}$$

through the following physical justification. While a bubble rises at U_B for a period of one shedding cycle, the solids in the wake decrease by an amount roughly proportional to the wake solids concentration times the discharged wake volume. The vortex shedding frequency can be approximated by the bubble rocking frequency (f_c) (Tsuchiya and Fan, 1988; Miyahara et al., 1988). Thus, if one knows the number of shedding/rocking cycles (N_m) before all the particles become depleted from the wake, H_m can be estimated from Eq. 1. f_c can be related to Re' ($= aU_t\rho_\ell/\mu_\ell$) through Sr as given in Figure 3.

U_B, the bubble rise velocity relative to the column, can be approximated by

$$U_B = U_t + U_\ell + U_w \tag{2}$$

based on the principle of velocity superposition. This principle has been successfully used in a theoretical prediction of the position and/or the rise velocity of the trailing bubble during its acceleration for two successive bubbles with laminar toroidal wakes (Crabtree and Bridgwater, 1971; Narayanan et al., 1974; Bhaga and Weber, 1980; Komasawa et al., 1980). In this prediction, the acceleration effect was accounted for by an additional velocity in the wake of the leading bubble, the so-called "wake velocity." U_w in Eq. 2 is the wake velocity and, in the present study, is regarded as the upward (i.e., toward the bubble base) velocity of liquid flow induced near the central axis of the wake at the nose of the trailing bubble. It is determined through an extension of the Schlichting's (1968) theory, which estimates the center-line velocity of a classical, free-stream potential wake behind a solitary body rising in a still liquid, to successive bubbles. U_w equals zero for a single-bubble system since there is no bubble-bubble interaction.

An empirical correlation is obtained in this study for N_m as a function of Re' as given below:

$$N_m = 1 \times 10^{-6}(Re')^{7/4} \tag{3}$$

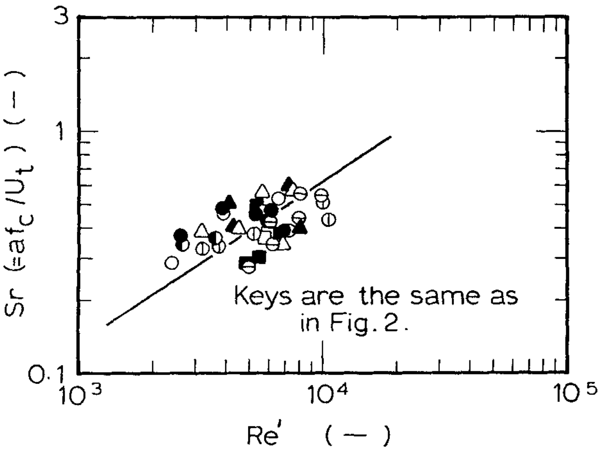

Figure 3. Bubble rocking frequency in the freeboard near the bed surface.

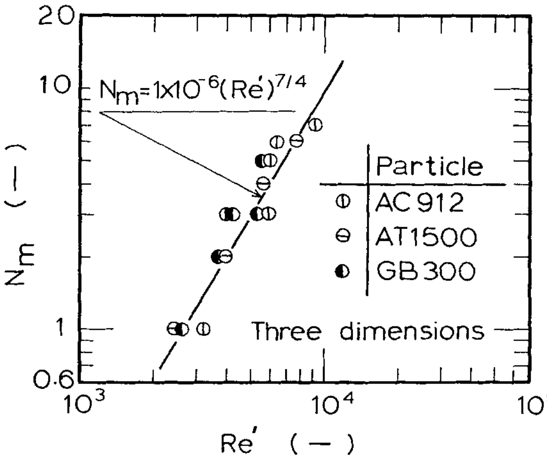

Figure 4. Number of bubble rockings for particle depletion in the bubble wake correlated in terms of the bubble Reynolds number.

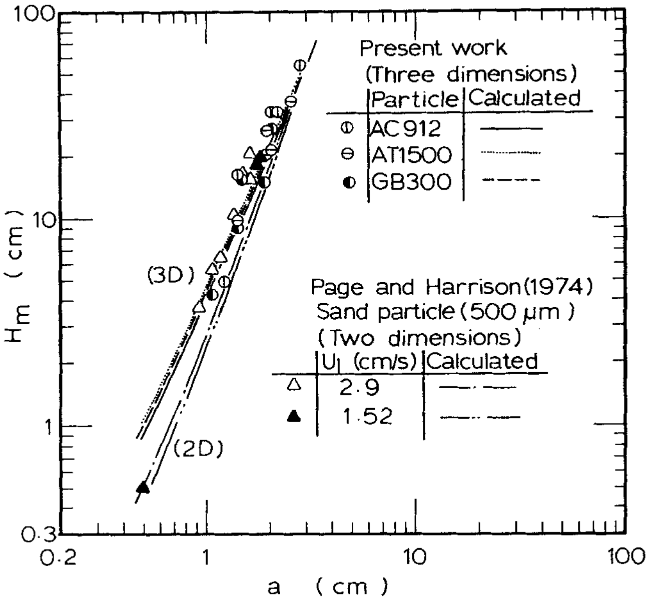

Figure 5. Maximum particle height entrained by a single bubble.

Figure 4 shows the relationship given by Eq. 3 which represents the data well for three types of particles considered in this study.

Based on Eqs. 1 and 3 and experimentally determined values of f_c and U_t, H_m is calculated and compared with experimental data for single bubbles of various sizes as shown in Figure 5. The experimental data include those obtained in a two-dimensional bed of Page and Harrison (1974) and those in the present three-dimensional system. Each value of H_m (from this study) plotted in the figure represents an average over measurements for three to five different runs under the same experimental condition and is reproducible within a ±10% error. As indicated in the figure, the difference betwen the data in the two- and three-dimensional systems is not significant, while the present model predicts slightly lower values in two dimensions than in three dimensions. Most importantly, the calculation satisfactorily represents the experimental data on H_m with reasonable accuracy, especially for the three-dimensional case.

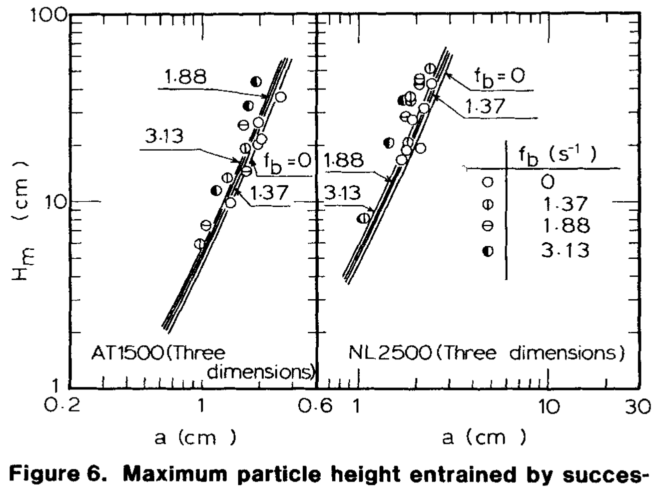

Figure 6. Maximum particle height entrained by successive bubbles.

For successive bubbles, the calculated H_m with U_w determined experimentally is compared with the experimental data for two types of particles as shown in Figure 6. The values for f_b are also shown in the figure. The calculated results reflect that H_m increases with an increase in f_b which is consistent with the trend exhibited by the experimental data. The fact that H_m can be reasonably predicted solely based on the near-wake behavior confirms that the bubble wake plays a dominant role in determining the maximum height of particle entrainment. In contrast, the drift has significantly less effect on the particle entrainment in the system.

Acknowledgment

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Notation

a = bubble major axis, cm
d = diameter of a sphere having the same volume as the bubble (3D case) or diameter of a circle having the same area as the bubble (2D case), cm
f_b = bubble formation frequency, s^{-1}
f_c = bubble rocking frequency, s^{-1}
H_m = maximum height of particle entrainment, cm
L_w = primary wake length, cm
N_m = number of bubble rockings for particle depletion in the bubble wake
Re = bubble Reynolds number = $dU_t\rho_\ell/\mu_\ell$
Re' = bubble Reynolds number = $aU_t\rho_\ell/\mu_\ell$
Sr = Strouhal number = af_c/U_t
U_B = apparent bubble rise velocity relative to the bed, cm/s
U_ℓ = superficial liquid velocity, cm/s
U_t = terminal rise velocity of a single bubble in infinite medium, cm/s
U_w = wake velocity of in-line bubbles, cm/s

Greek letters

μ_ℓ = liquid viscosity, poise
ρ_ℓ = liquid density, g/cm^3

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