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Dynamic Characteristics of Bed Collapse in Three-Phase Fluidized Beds

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Abstract−Transient behavior of the bed collapse after shut-off the gas supply into a three-phase fluidized bed was determined. Experiments were carried out in a 210-mm diameter half-tube acrylic column having a 1.8 m-high test section. The polymer beads (d_p=3.2 mm, ρ_s=1,280 kg/m^3) were fluidized by cocurrent flow of deionized water and air. The transient behavior of the bed collapse after cut-off the gas supply to the bed was monitored by a video camera (30 frames/s). The dense bed surface height was measured from the image of videotape. At lower liquid velocity, the dense bed surface increases with the elapsed time and then reaches a bed height, whereas at higher liquid velocity the dense bed surface increases sharply with the elapsed time, then decreases and reaches the bed height corresponding to the liquid-solid fluidized beds (water-polymer beads).

Key words: Bed Collapse, Three-Phase Fluidized Beds, Dynamic Characteristics, Dense Bed Height

INTRODUCTION

Fluidization refers to a process by which a fluid-like state is imparted to granular solid particles by the application of appreciable forces [Kwauk, 1992]. Three-phase fluidization is defined as an operation in which a bed of solid particles is suspended in gas and liquid upward flowing media due to the net drag force of gas and/or liquid flowing opposite to the net gravitational force on the particles [Lee et al., 1993; Park and Kim, 2003]. In most three-phase fluidized beds, liquid flows as the continuous phase and both gas bubbles and solid particles as the dispersed phase. Three-phase fluidized beds have been applied to many industrial processes, such as hydrogenation and the Fisher-Tropsch process, to name but a few [Fan, 1989; Han et al., 2003; Lee et al., 2000].

Jin and Zhang [1990] also conducted bed collapsing experiments to determine the parameters of k and x in the generalized wake model [Bhatia and Epstein, 1974] of three-phase fluidized beds. Chen and Fan [1990] presented a theory to explain the dynamic behavior of bed collapse in three phase fluidized beds after a sudden stop of gas and liquid flows. They also reported that the predicted dynamic behavior of the bed collapse by the proposed theory agrees well with the experimental data. In their theory, they assumed that no bubble is trapped in the liquid-solid packed bed region and the liquid-solid sedimentation region after a sudden stop of the gas and liquid flows. However, previous studies [Maucci et al., 1999; Fan, 1999] found that many bubbles are trapped in the liquid-solid packed-bed region since heavy particles quickly move downward.

The objective of this study is to determine the dynamic behaviors of the bed collapse in a three-phase fluidized bed after a sudden stop of gas supply at a constant liquid flow rate above the minimum fluidization velocity in the liquid-solid fluidizing system.

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EXPERIMENTAL

Experiments were performed in a 210-mm diameter half-tube acrylic column having a 1.8 m-high test section. The schematic diagram of the experimental setup is shown in Fig. 1. The particles used

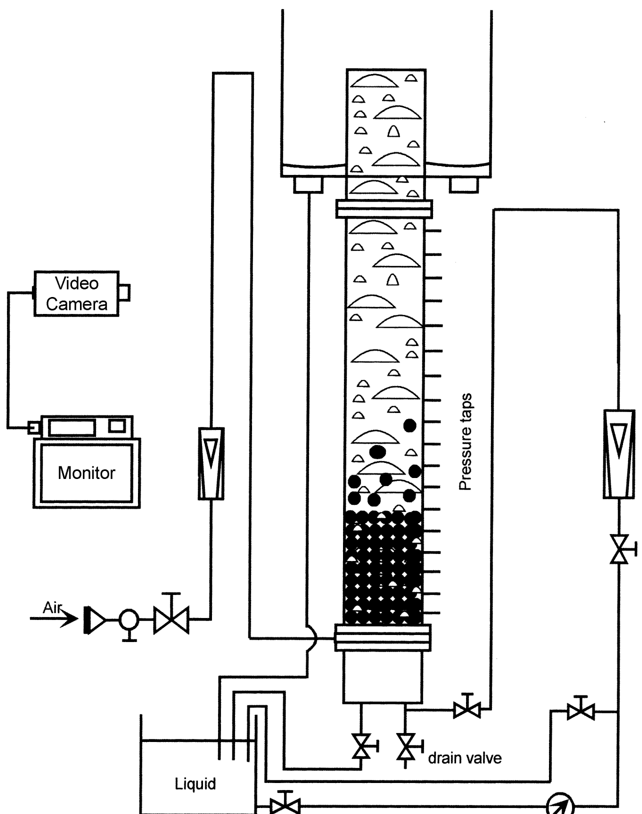

Fig. 1. Schematic diagram of experimental equipment.

were 3.2 mm polymer beads (ρ_s=1,280 kg/m^3) as the solid phase. Deionized water and air were used as the liquid and gas phase, respectively. The particles were fluidized by cocurrent up flow of liquid and gas phases. The static bed height (H_{B0}) was always maintained higher than 0.5 m regardless of the particle density. The gas (0.0-28.9 mm/s) and liquid (0.0-33.0 mm/s) flow rates were measured by flowmeters. The liquid was introduced into the plenum chamber in which 16-mm glass raschig rings were packed and then through a perforated liquid distributor plate containing 35 evenly spaced holes (3 mm) into the main fluidized bed. Air was injected into the bed through ten evenly spaced perforated feed pipes with 33 upward-facing holes of 1.0 mm diameter on top of the liquid distributor. Dynamic pressures in the bed were measured by differential pressure transducers (GP : 50, model: 316X) connected to the pressure taps which were mounted flush with the column wall at 0.1 m height intervals starting from 0.05 m above the liquid distributor. The transducer signals were processed by a PC at a sampling frequency of 1 Hz with time intervals of 180 s.

The individual phase holdups were determined from the knowledge of the static pressure drop, expanded bed height and solid weight in the bed as:

$$-\frac{\Delta P}{\Delta z}=(\varepsilon_g\rho_g+\varepsilon_l\rho_l+\varepsilon_s\rho_s)g \tag{1}$$

$$\varepsilon_g+\varepsilon_l+\varepsilon_s=1.0 \tag{2}$$

$$\varepsilon_s=\frac{M_p/\rho_s}{\pi/4D_t^2 1/2H_B} \tag{3}$$

In the dynamic experiments, the system was first operated at the given gas and liquid flow rates to maintain steady state. Thereafter, a ball valve in the gas supply line was quickly closed to shut-off the gas supply and then the expanded bed height was suddenly collapsed. The transient behavior of the bed collapse after shut-off the gas supply was monitored by a video camera with a frame speed of 30 frames/s. The dense bed surface was measured by analyzing the pictures in the videotape.

RESULTS AND DISCUSSION

One sample of the bed collapse process was monitored by a video camera as shown in Fig. 2. As can be seen, the height of the dense bed is not clear since it is disturbed by bubble movements. Vagueness of the bed surface is also attributed to the entrained particles before cutting-off the air supply (t≤0 s) and those particles move downward due to gravity after cutting off of the air supply. As can be seen in Fig. 2, height of the dense bed increases with increasing elapsed time after cut-off of the air supply at a constant liquid velocity (U_l=19.8 mm/s). Jin and Zhang [1990] have classified the bed

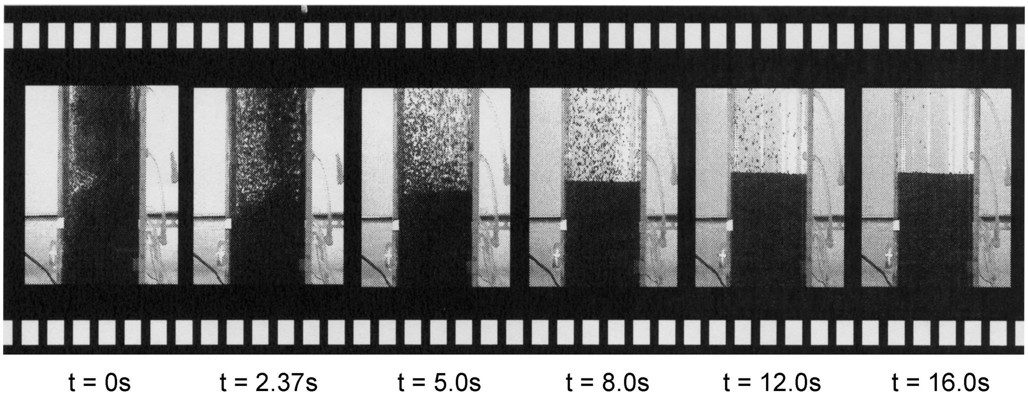

Fig. 2. Series of snapshot on H_{db} after shutting off of the gas supply at U_l=19.8 and U_g=19.4 mm/s.

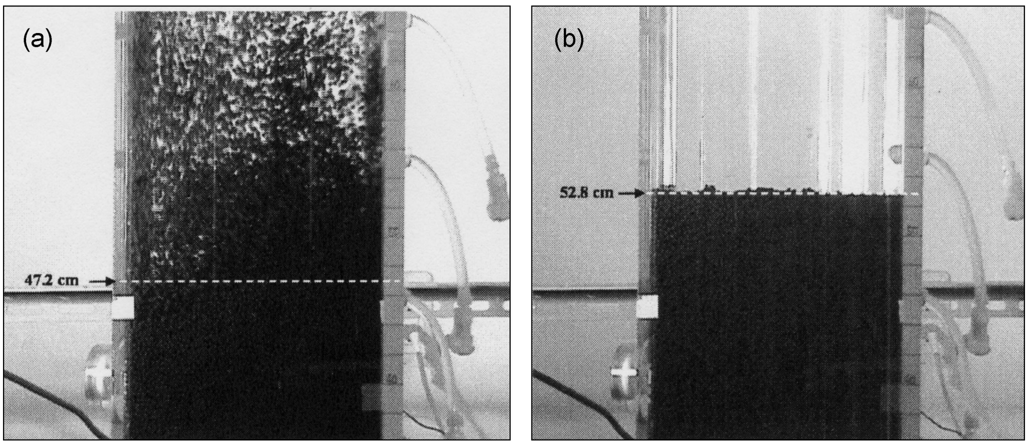

Fig. 3. Typical snapshots for determining the dense bed height after shutting-off of the gas supply: (a) snapshot at t=2.47 s after shutting-off of the gas supply, (b) snapshot at t=20 s after shutting-off the gas supply.

collapse process into three stages after cutting off the air supply. At the first stage, the bed surface collapses very quickly, which corresponds to the bubble escaping process. At the second stage, voidage of the liquid-solid fluidization region gradually attains particulate liquid-solid fluidization. At the third stage, the bed turns into steady particulate liquid-solid fluidization. However, as reported by Jin and Zhang [1990], the height of the dense beds increases with increasing elapsed time after cut-off of the air supply since solid holdup in the liquid-solid fluidization region of three-phase fluidized beds is higher than that in the particulate liquid-solid beds.

Typical snapshots to determine the dense bed height after shutting-off the gas supply are shown in Fig. 3, where the dense bed heights are 47.2 cm at t=2.47 s and 52.8 cm at t=20 s after the gas supply is shut off. As can be seen in Fig. 3(a), vagueness of the dense bed surface can also be attributed to the entrained particles which move downward due to gravity after the air supply is cut off. However, as can be seen in Fig. 3(b), the dense bed surface at t=20 s is much clear than that at t=2.47 s after the gas supply is shut off. When the dense bed surface was unclear, each frame was inspected frame by frame.

A typical axial pressure drop profile before the air supply is cut off ($t \leq 0$ s) in a gas-liquid three-phase fluidized bed is shown in Fig. 4. In a bed of finer and/or lighter solids (e.g., glass beads smaller than 1 mm) that are fluidized by air and water, the upper bed surface becomes increasingly diffuse at higher fluid velocities, primarily due to particle entrainment, but also due to stratification of solids by its size [Epstein, 1981]. Referring to Fig. 4, a reproducible value of the bed height (H_B) can be obtained from the intersection of two straight lines, one of the positive slope represents the pressure profile in the constant voidage region of the three-phase bed, which terminates at H_{db}, and the other of negative slope represents the pressure drop profile in the solid-free two-phase region above the bed. As pointed by Epstein [1981], the point of H_{db} in Fig. 4 is the dense bed height.

Variation of the dense bed height with the elapsed time after the gas supply is cut off shown in Fig. 5. As can be seen, at lower liquid velocities (U_l=19.8 mm/s), the height of the dense beds increases with the elapsed time and then reaches the bed height corresponding to liquid-solid fluidized beds. When the air supply is cut off,

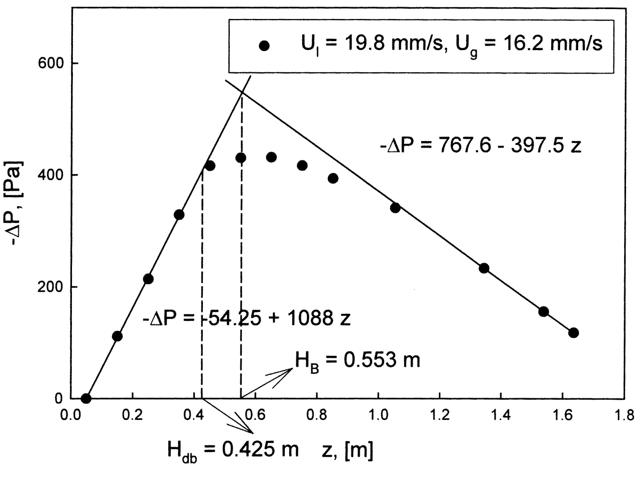

Fig. 4. Typical axial pressure drop profile before shutting-off of the gas supply ($t \leq 0$ s).

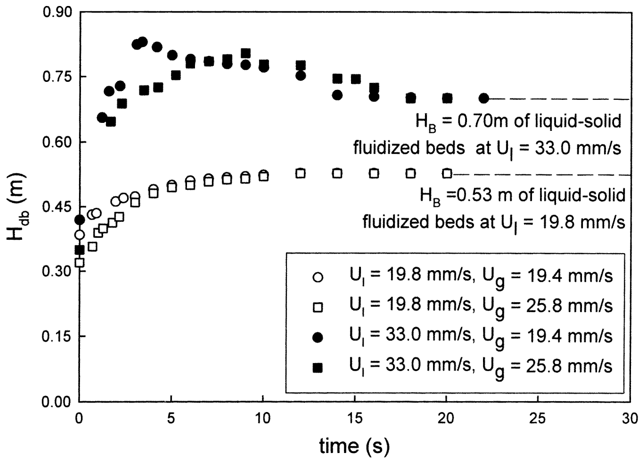

Fig. 5. Variation of H_{db} with the elapsed time.

bed voidage of the liquid-solid fluidization region of the three-phase bed gradually attains the particulate liquid-solid fluidization. As pointed by Jin and Zhang [1990], solid holdup in the liquid-solid fluidization region of three-phase beds is greater than that in the corresponding liquid-solid fluidized beds at the same superficial liquid velocity, so that the dense bed height gradually rises to the height of the corresponding liquid-sold fluidized beds. Based on the generalized wake model [Bhatia and Epstein, 1974], the liquid velocity of wake region is equal to the rise velocity of gas bubbles. After the air supply is cut-off, liquid holdup of the wake region decreases with the elapsed time since gas bubbles have gone up and disappeared. The liquid velocity in the liquid-solid fluidization region increases with the elapsed time. Therefore, the dense bed height increases with increasing liquid velocity in the liquid-solid fluidization region and then reaches the bed height corresponding to liquid-solid fluidized beds. However, at higher liquid velocities (U_l=33.0 mm/s), height of the dense bed surface increases sharply initially, decreases with elapsed time, and then reaches the bed height of the corresponding liquid-solid fluidized beds. This phenomenon is different from the results of Jin and Zhang [1990] and Chen and Fan [1990]. Both of them used glass beads ($\rho_s \cong 2{,}500$ kg/m^3) as the solid particles, whereas polymer beads (ρ_s=1,280 kg/m^3) having lower density than that of glass beads were used in the present study. At higher liquid velocity, polymer beads are severely suspended due to momentum of the gas bubbles. After a sudden stop of gas supply, similar to the case of lower liquid velocity, liquid holdup of the wake region decreases with the elapsed time since gas bubbles go upward and disappear rapidly. The liquid velocity in the liquid-solid fluidization region increases with the elapsed time. Therefore, the dense bed height increases with increasing liquid velocity in the liquid-solid fluidization region. Also, the suspended particles move down slowly due to decreasing momentum of the gas bubbles. Hence, both of them attribute a higher dense bed height compared to that of the corresponding liquidsolid fluidized beds. Thereafter, the dense bed height decreases and reaches the bed height corresponding to liquid-solid fluidized beds owing to the gravity of polymer beads.

CONCLUSION

The transient behaviors of the bed collapse after shutting-off the gas supply in three-phase fluidized beds have been determined. At lower liquid velocities, the height of the dense bed surface increases with the elapsed time and then reaches the bed height of the corresponding liquid-solid fluidized beds. However, at higher liquid velocities, the height of the dense bed surface increases sharply with the elapsed time, decreases, and then reaches the bed height of the corresponding liquid-solid fluidized bed.

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NOMENCLATURE

D_t : column diameter [m]
g : acceleration of gravity [m/s^2]
H_B : bed height [m]
H_{B0} : static bed height [m]
H_{db} : dense bed height [m]
M_p : particle inventory [kg]
$-\Delta P$: total pressure drop [Pa]
$-\Delta P/\Delta z$: total pressure gradient [Pa/m]
t : elapsed time after cut-off the air supply [s]
U_g : superficial gas velocity [mm/s]
U_l : superficial liquid velocity [mm/s]
z : axial bed height [m]

Greek Letters

ε_g : gas holdup [-]
ε_l : liquid holdup [-]
ε_s : solid holdup [-]
ρ_g : gas density [kg/m^3]
ρ_l : liquid density [kg/m^3]
ρ_s : particle density [kg/m^3]

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