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Slug Characteristics of Polymer Particles in a Gas-Solid Fluidized Bed

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Abstract−The slug characteristics (frequency, rising velocity and length) have been determined by analyzing pressure fluctuations in a fluidized bed (0.38 m-I.D.×4.4 m-high) of linear-low-density-polyethylene (LLDPE) and polypropylene (PP) particles. The slug characteristics of LLDPE and PP particles have been determined as a function of gas velocity (0.6-1.2 m/s) and the axial height (0.65-1.15 m) from the distributor. The rising velocity and vertical length of slug increase with increasing superficial gas velocity and the axial height of the bed. The slug shape of LLDPE particles is found to be the square-nose whereas that of PP particles is the round-nose. The slug frequency and its length have been correlated in terms of the excess fluidizing velocity, column diameter and bed height based on the data from the present and previous studies.

Key words: Slug Frequency, Slug Rising Velocity, Polymer Particles, Gas Fluidized Bed

INTRODUCTION

Fluidized beds have been using widely in industrial processes such as combustor, gasifiers, fluid catalytic cracking (FCC) regenerator, name but a few. Fluidized bed reactor can be utilized for the gas-phase polymerization of ordinary polymer resins such as linearlow-density polyethylene (LLDPE) and polypropylene (PP) since no separation is needed between the products and the catalysts that used as seed particles. In the fluidized bed of polymer powders, particle agglomeration occurs due to static electricity that comes from frictions of particles to particles and particles to the column wall, hence sintering and softening of particles occur [Boland and Geldart, 1971]. Therefore, fluidizing behavior is shifted to channeling from bubbling and increases pressure drop in the beds [Davidson and Harrison, 1977; Geldart, 1986]. Moreover, uniformity of fluidization may affect particle mixing and distribution of bubble or slug in the beds. This non-uniformity may cause dead zone and hotspots and consequent unstable operation of the polymerization process.

In the polymer production in a fluidized bed reactor, bubble size increases rapidly to form slugs with increasing gas velocity. Therefore, it is very important to determine the slugging characteristics in a fluidized bed of polymer particles. Many studies have been published on the slug characteristics in fluidized beds by measuring pressure fluctuations [Baeyens and Geldart, 1974; Broadhurst and Becker, 1975; Cho et al., 2001; Lee and Kim, 1988; Noordergraaf et al., 1987; Satija and Fan, 1985] and movie photographic technique [De Luca et al., 1992]. They proposed correlation to predict slug frequency of different particles such as FCC catalyst, glass beads and iron particles (Table 1).

In the present study, the slug characteristics of polymer particles in a comparatively large three-dimensional bed have been determined as a function of the gas velocity along the bed height. The slug frequency and its length obtained in the present and previous studies have been correlated in terms of the excess fluidizing velocity, column diameter and bed height.

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Table 1. Summary of slug frequency and slug length in the literature

Authors	Correlation equation
Baeyens and Geldart [1974]	$f_L=\frac{0.35g^{1/2}}{k_L D_t^{1/2}}$ for $k_L=\frac{9.38}{D_t^{0.357}}$
Nakamura and Capes [1977]	$L_s=2.6(U_g-U_{mf})^{0.48}H^{0.22}$ (H≤1.2 m)
	$L_s=0.47(U_g-U_{mf})^{0.78}H^{0.46}$ (H>1.2 m)
Shichun et al. [1985]	$f=0.533(U_g-U_{mf})^{-0.152}$
	$L_s=2.17U_g^{1.31}(U_g-U_{mf})^{-0.16}$
Noodergraaf et al. [1987]	$f=0.32U_g^{-0.15}H_o^{-1.0}$
De Luca et al. [1992]	$\frac{fH_{mf}}{U_g-U_{mf}}=0.17\left[\frac{gD_t}{(U_g-U_{mg})^2}\right]^{2/3}+0.1$
	$\frac{L_s}{\sqrt{gD_t}}=2.09\frac{U_g-U_{mf}}{\sqrt{gD_t}}-0.37$

EXPERIMENTAL

Experiments were carried out in a fluidized bed (0.38 m-I.D.×4.3 m-high) and the details can be found elsewhere [Lee et al., 2001].

Table 2. Physical properties of particles

Experimental particles	L-LDPE	PP
Mean diameter, [μm]	1,230	600
Density, [kg/m³]	919	900
Minimum fluidization velocity, [m/s]	0.30	0.13
Minimum slugging velocity, [m/s]*	0.42	0.27

*Calculated by the method of Kunii and Levenspiel [1991].

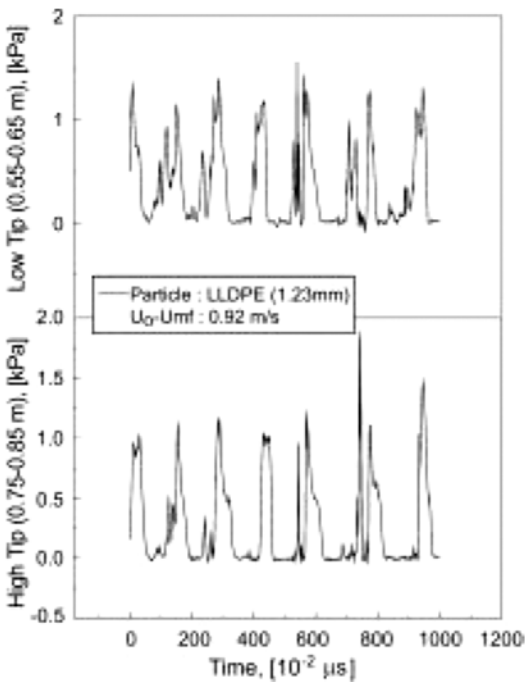

Fig. 1. Typical response signals of pressure fluctuations.

The particles studied were 1.23 mm LLDPE (919 kg/m^3) and 0.6 mm PP (900 kg/m^3) particles. The distributor used in the present study was a 5 mm-perforated plate to provide uniform air distribution in the bed [Lee et al., 2001]. The physical properties of solids particles are listed in Table 2. Pressure taps were mounted flush with the wall of the column at 0.1 m height intervals from 0.55 m above the distributor. The taps were connected to the differential pressure transducers. Pressure fluctuation signals from the transducer were monitored by a personal computer at a frequency of 100 Hz for 60s.

Typical pressure fluctuation signals are shown in Fig. 1 in which the signals can be divided into emulsion and slug phases by a reference value [Lee et al., 2001]. The slug characteristics (slug frequency, slug rising velocity and slug length) are calculated by the pressure fluctuations as [Lee et al., 2001]

Individual slug rising velocity (U_{si}) is

$$U_{si} = \frac{\text{distance between two taps}}{T_i} \tag{1}$$

where T_i is time for individual slug.

The average slug rising velocity (U_s) is

$$U_s = \frac{1}{n}\sum_{i=1}^{n} U_{si} \tag{2}$$

The slug frequency (f) is calculated by

$$f = \frac{\text{n(number of slugs)}}{\text{T(total sampling time)}} \tag{3}$$

The individual slug length (L_i) and the average slug length (L_s) are calculated by

$$L_i = U_{si} \times S_i \tag{4}$$

$$L_s = \frac{1}{n}\sum_{i=1}^{n} L_i \tag{5}$$

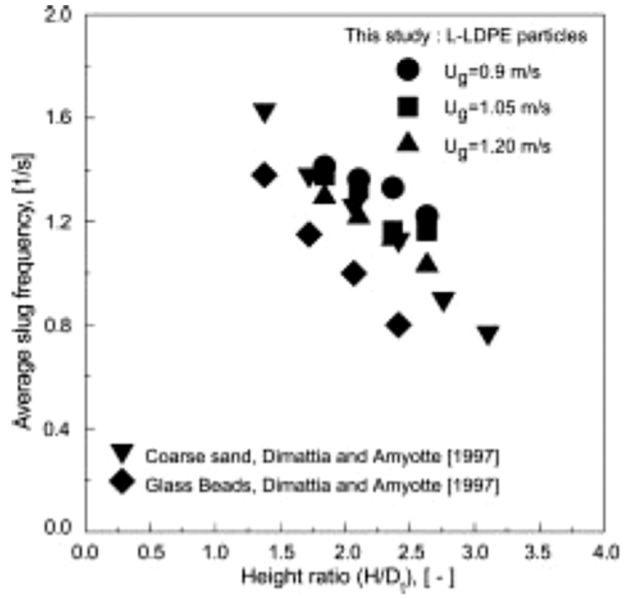

Fig. 2. The average slug frequency as a function of the expanded bed height.

RESULTS AND DISCUSSION

Variations of the average slug frequency in the bed of LLDPE particles along the bed height ratio (H/D_t) are shown in Fig. 2. As can be seen, slug frequency decreases with increasing the bed height. It has been reported that slug frequency decreases with increasing static bed height because a single slug must pass through an increased volume of particles [Dimattia and Amyotte, 1997; Noordergraaf et al., 1987; Satija and Fan, 1985; Verloop and Heertjes, 1973]. However, slug frequency does not change in the shallow and small column diameter beds [Baeyens and Geldart, 1974]. In a fluidized bed, bubbles grow in size to become slugs along the bed height due to

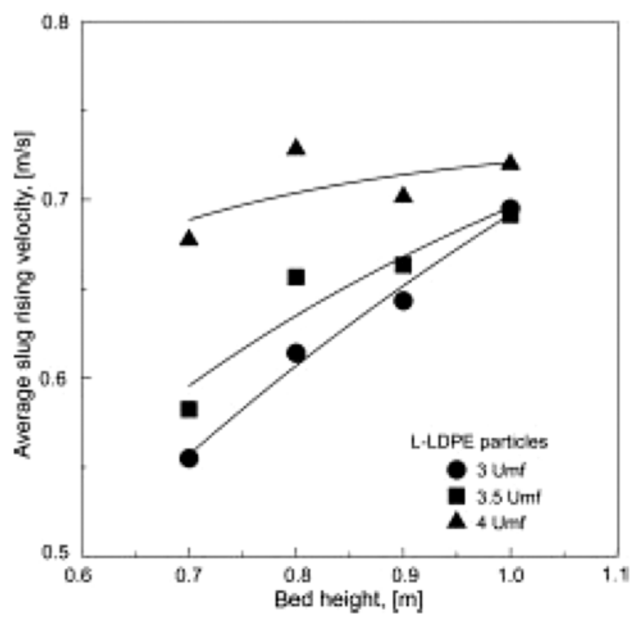

Fig. 3. The average slug rising velocity as a function of the expanded bed height.

bubble coalescence and slug size also increase with the bed height. Therefore, slug frequency consequently decreases with its size along the bed height.

The slug rising velocity in the bed of LLDPE particles along the bed height is shown in Fig. 3. As can be expected, slug rising velocity increases with increasing the bed height due to bubble or slug coalescence that produce larger slugs having faster rising velocity. Dry et al. [1984] reported that slug rising velocity is affected by gas velocity and column diameter but the effect of bed height on slug rising velocity is found to be negligible. Whereas, Nakamura and Capes [1977] reported that slug rising velocity is affected by the bed height due to the increase of slug size. Although slug rising velocity increases with the bed height, the increasing rate of slug rising velocity decreases with increasing gas velocity due to the wall effect.

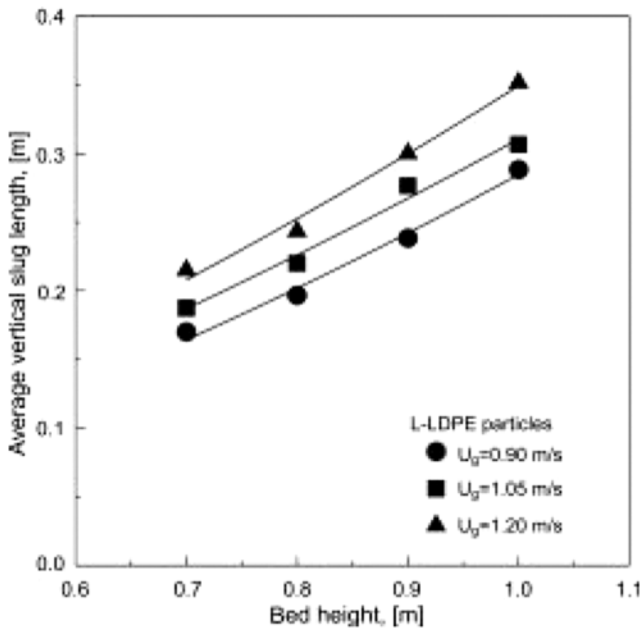

Fig. 4. The average slug length as a function of the expanded bed height.

The effect of the bed height on the average slug length is shown in Fig. 4. As can be seen, slug length increases with increasing the bed height due to bubble or slug coalescence. Since the breakage of slug of LLDPE particles less occurs than that of bubbles in fluidized beds, and slug length hence increase up to the bed surface. Nakamura and Capes [1977] reported that slug length and its velocity are influenced by the bed height based on the bubble coalescence theory. It has been also reported that slug length is influenced by bed diameter and the minimum fluidization bed height [De Luca et al., 1992].

The effect of gas velocity (U_g) on slug frequency in the bed of different particles is shown in Fig. 5. Slug frequency in the bed of PP particles decreases linearly with increasing U_g as found previously [Lee et al., 2001; Satija and Fan, 1985; Shichun et al., 1985]. Noordergraaf et al. [1987] reported that the obtained slug frequencies are much higher in the bed of glass beads than that of sand particles having square-nose slugging. According to Baeyens and Geldart [1974], slug frequency is not affected by the particle property. However, Satija and Fan [1985] claimed that slug frequency of coarse particles is lower than that of fine particles in the same column diameter.

The effect of gas velocity (U_g) on slug rising velocity of different particles is shown in Fig. 6. Noodergraaf et al. [1987] reported two types of slug, namely round-nose and square-nose and the majority of publications on slug properties deal with the round-nose slug that is the characteristics of fluidized beds of small particles. In case of square-nose slug, slug rising velocity is lower than the superficial gas velocity and particles continuously rain through slug in the bed. Similarly to LLDPE particles, slug rising velocity of PP particle increases linearly with increasing U_g. As can be seen, the slopes of slug rising velocities of PP particles, FCC and iron metal powders are higher than that of superficial gas velocities in the bed. However, the slope of slug rising velocities of LLDPE particles are

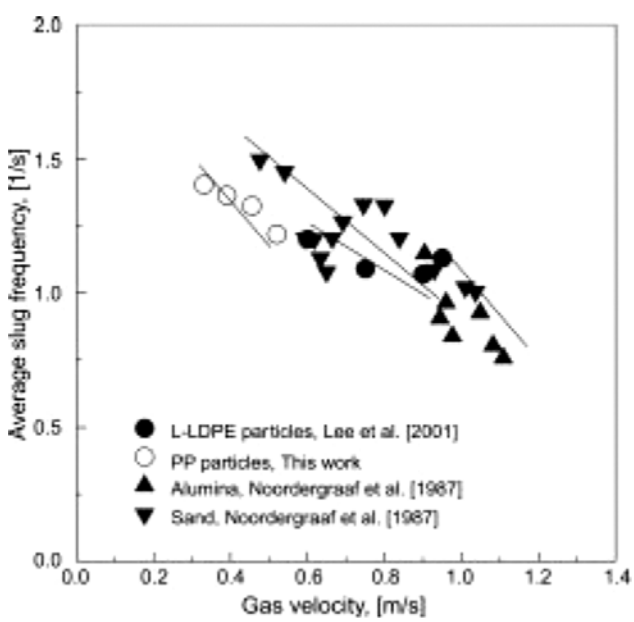

Fig. 5. Effect of gas velocity on the average slug frequency.

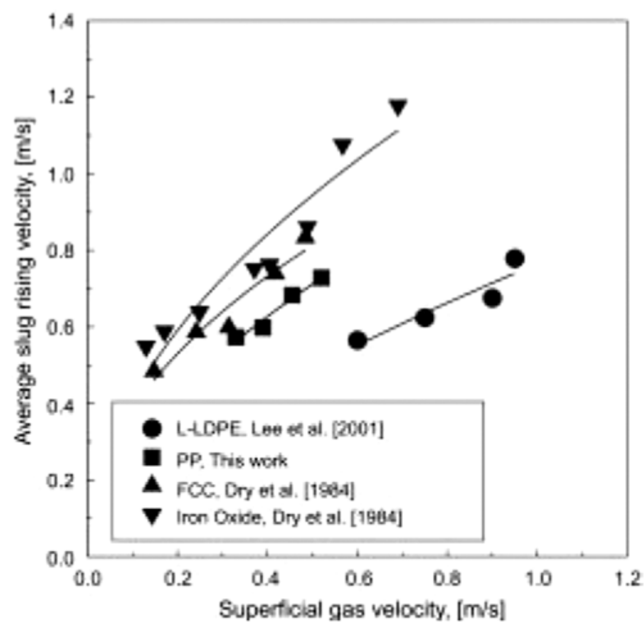

Fig. 6. Effect of gas velocity on the average slug rising velocity.

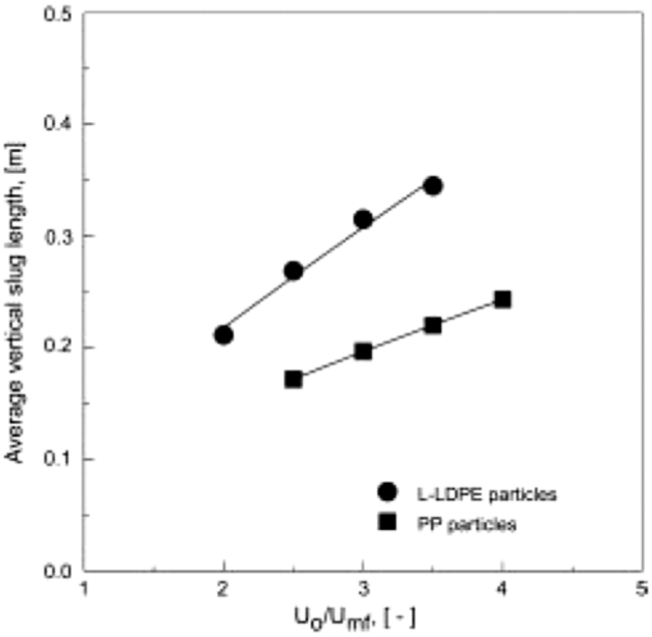

Fig. 7. Effect of gas velocity (U_g/U_{mf}) on the average slug length.

lower than that of the superficial gas velocities according to the slug types [Lee et al., 2001]. As observed visually, the slug shapes of PP and L-LDPE particles are respectively round-nose and square-nose slugs due to the particle properties.

The effect of gas velocity (U_g/U_{mf}) on the average slug length is shown in Fig. 7 where slug length increases with increasing gas velocity. Slug length of LLDPE particles is longer than that of PP particles due to the different slug shapes. Slug rising velocity increases with its size and increasing gas velocity as found previously [Nakamura and Capes, 1977; Shichun et al., 1985]. Matsen et al. [1969] and Satija and Fan [1985] reported that slug frequency and slug length increases with increasing gas velocity and consequent increase in expanded bed height.

The relationships among the average vertical slug length, the average slug frequency, and the average slug rising velocity are shown in Fig. 8. As can be seen, the average slug frequency decreases with increasing slug length. However, the average slug rising velocity increases with increasing slug length. As the superficial gas velocity is increased and consequent increase in expanded bed height, bubble or slug coalescence occurs frequently [Lee et al., 2001; Nakamura and Capes, 1977; Noodergraaf et al., 1987]. Thus, the slug rising velocity increases with the vertical slug length [Nakamura and Capes, 1977]. The slug frequency decreases with gas velocity and the expanded bed height (Figs. 2 and 5).

To predict the slug length and frequency, several correlations have been proposed by previous investigators [Baeyens and Geldart, 1974; Brodhurst et al., 1983; Matsen et al., 1970; Nakamura and Capes, 1977; Satija and Fan, 1985; Shichun et al., 1985]. However, the reported correlations could not fit the present experimental data due to the difference of powder properties employed such as the Geldart A and B particles [Baeyens and Geldart, 1974; Brodhurst et al., 1983; Matsen et al., 1970; Nakamura and Capes, 1977; Shichun et al., 1985]. Slug length and slug frequency are known as a function of U_g, column diameter and the bed height. Therefore, slug length and slug frequency have been correlated in terms of the excess fluidizing velocity, column diameter and bed height from the experimental data of present and previous studies [Satija and Fan, 1985; Noodergraaf et al., 1987; Luca et al., 1992; Lee et al., 2001] as:

$$fH_{mf}=0.25\left(\frac{gD_t}{U_g-U_{mf}}\right)^{0.63} \tag{6}$$

$$\frac{L_s}{\sqrt{D_tH_{mf}}}=1.77\left(\frac{U_g-U_{mf}}{gD_t}\right)^{1.33} \tag{7}$$

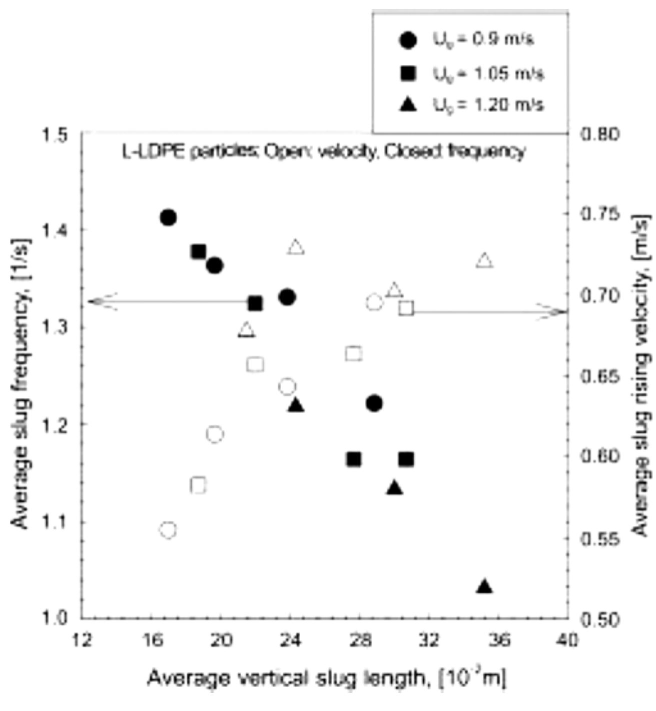

Fig. 8. Relationships among the average slug length and the average slug rising velocity and the average slug frequency.

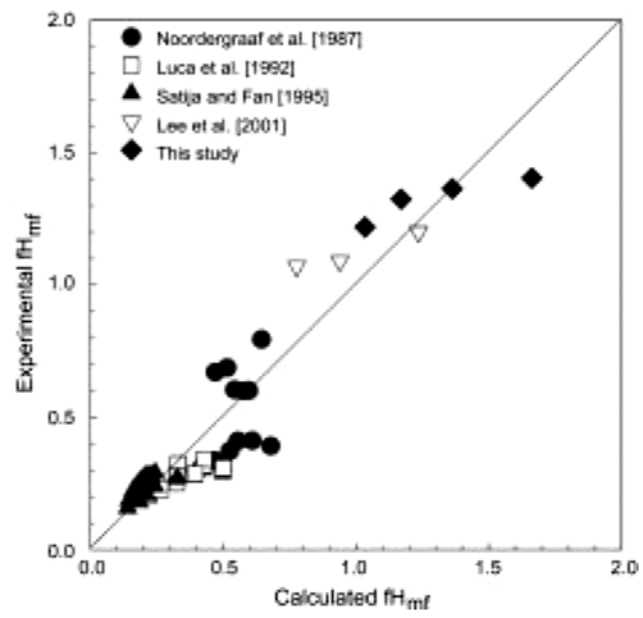

Fig. 9. Parity plot of fH_{mf} predicted from Eq. (6) with the data of the present and previous studies in gas-solid fluidized beds.

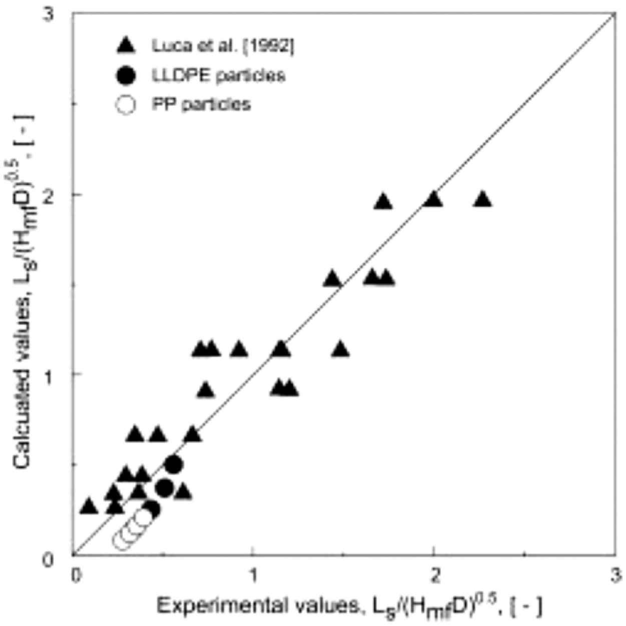

Fig. 10. Parity plot of $L_s/(D_tH_{mf})^{0.5}$ predicted from Eq. (7) with the data of the present and previous studies in gas-solid fluidized beds.

with the correlation coefficients of 0.93 and 0.94, respectively. Eqs. (6) and (7) cover the experimental ranges of $0.1 \le D_t \le 0.38$ m, $0.2 \le H_{mf} \le 1.00$ m and $0.6 \le U_g \le 3.6$ m/s.

As can be seen in Figs. 9 and 10, the predicted values of slug frequency and slug length from Eqs. (6) and (7) are well accord to the experimental data of the present and previous studies [Lee et al., 2001; Luca et al., 1992; Noodergraaf et al., 1987; Satija and Fan, 1985].

CONCLUSION

The slug rising velocity and slug length increase, but slug frequency decreases with increasing gas velocity and expanded bed height due to the slug or bubble coalescence. The slug shape of LLDPE particles is found to be the square-nose while that of PP particles is the round-nose in the bed. The slug frequency decreases with slug length and its rising velocity and slug rising velocity increases with slug length. The obtained and reported slug frequency and slug length have been correlated in terms of the excess fluidizing velocity, column diameter and bed height.

NOMENCLATURE

D_t : column diameter [m]
f : slug frequency [s^{-1}]
f_L : slug limiting frequency [s^{-1}]
g : gravitational acceleration [m/s^2]
H : bed height [m]
H_{mf} : bed height at minimum fluidization [m]
L_s : slug length [m]
L_i : individual slug length [m]
n : number of slug [-]
S_i : duration of ith slug [s]
T : sampling time [s]
U_g : superficial gas velocity [m/s]
U_{mf} : minimum fluidization velocity [m/s]
U_s : average slug rising velocity [m/s]
U_{si} : individual slug rising velocity [m/s]

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