HYDRODYNAMIC CHARACTERISTICS OF A CIRCULATING FLUIDIZED BED

Gui Young Han, Geun Seong Lee and Sang Done Kim*

Department of Chemical Engineering, Korea Advanced Institute of Science and Technology, Seoul 131, Korea

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Abstract— In a circulating fluidized bed (7.8 cm-ID × 260 cm-high), flow regime of coal-air system at room temperature has been determined.

Bituminous coal particles used were either 0.73 mm or 1.03 mm in the mean diameter having density of 1400 Kg/m^3.

The transition velocities from bubbling to turbulent beds and the transport velocities between turbulent and fast beds have been determined. The resulting transition velocities between bubbling and turbulent beds were 103 cm/s for 0.73 mm and 130 cm/s for 1.03 mm coal particles, respectively. The transport velocities between turbulent and fast beds were 180 and 209 cm/s for 0.73 and 1.03 mm particles, respectively.

In addition, chocking velocities were determined at different solid feeding rates. The resulting values were in the range of 2.55-2.65 m/s for 0.73 mm particle and of 2.77-2.84 m/s for 1.03 mm particle, respectively.

The published literature data of the transition velocity between bubbling and turbulent bed have been correlated with particle properties.

INTRODUCTION

In order to circumvent the disadvantage of the conventional combustion processes, several fluidized bed combustors have become the subject of intense research and development efforts in recent years.

One of the promising fluidized bed combutor is the circulating fluidized bed which is claimed to have excellent contacting between the solids and fluid and high processing capacity with low emission of sulfur dioxide and nitric oxides.

Consider a fluidized bed maintained at minimum fluidizing condition. As the fluidizing gas velocity increases slowly, bubble appear, and the bubbling activity intensifies due to the increase of bubble size and its frequency of formation. With further increase of gas velocity, the heterogeneous two phase flow begins to change toward a condition of increasing homogeneity until a point is reached at which large bubbles are on the absent. This condition can be termed as the onset of the turbulent regime. The absence of large bubbles in the turbulent bed may afford better contacting between gas and solid. As the fluidizing gas velocity approaches the transport velocity, there is a sharp increase in the carry-over rate, and without the recycle of carry-over solids, the bed would empty in a short period of time. The fast fluidized bed is an entrained dense suspension in which considerable backmixing of solid in the form of refluxing of clusters and streamers of particles. The fast fluidized bed may have the following advantages over the bubbling fluidized bed; 1) the temperature is uniform throughout the fast bed [4], this is a consequence of the high degree of solids mixing in the fast bed [5,13], 2) the fast bed is capable of bringing a cold solid or gas feed almost instantaneously to the bed temperature [13,15-18], 3) heat transfer rates to wall and immersed surfaces in the fast bed are comparable to those for a bubbling fluidized bed [2,15], 4) high processing capacity [13,15-18], 5) the fast bed affords excellent contact between gas and solids [3,6,7] which provides excellent carbon burnout and high desulfurization efficiency at low Ca/S mole ratio [9], 6) the high gas velocities preclude appreciable backmixing of gas so that the operation might approach a plug flow condition [2,15], 7) the fast bed ought to handle cohesive solids that might be difficult to fluidize in the bubbling bed [2,15-18], 8) the fast bed might prove easier to scale up than bubbling bed [15-18], 9) in the fast bed, the combustion results in smaller excess air for complete combustion and reduced nitrogen oxides emission [9].

Therefore, the objective of this study is to determine the hydrodynamic characteristics of a circulating fluidized bed such as minimum fluidizing velocity, the transition velocities between bubbling and turbulent beds and

* To whom all correspondence should be addressed.

Table. 1. Experimental Ranges of the Variables

Particle Size (d_p)	: 0.73, 1.03mm
Superficial Air Velocity	: 1.4 − 350cm/s
Recycle rate	: 20 − 40Kg/hr.
Feeding rate for Choking Condition	: 30 − 50Kg/hr.

between turbulent and fast fluidized beds. In addition, chocking velocity in the given bed of solids have been determined.

EXPERIMENTAL

The coal used were *either* 0.73 mm (0.601-0.894 mm) *and* 1.03 mm (0.894-1.17 mm) bituminous coal with density of 1.4 g/cm^3.

Experiments were carried out in a stainless steel column of 7.8 cm-ID × 260 cm-high. The details of the equipment and the particle size distributions were described previously [4]. Initially, the bed was loaded with 3,100 cm^3 of coal through the feeding port at the top of the bed. Oil-free compressor air was fed to the column at the desired superficial velocities through a pressure regulator and a calibrated rotameter.

In the bubbling and turbulent fluidized beds conditions, the recycle line should be closed. Whereas, in a circulating fluidized bed condition, same amount of coal in the main bed was loaded into the auxilliary bed for recycle. When steady state was reached, the pressure profile up to the entire height of the column was measured using the water manometers.

Experimental variables in the present study are shown in Table 1.

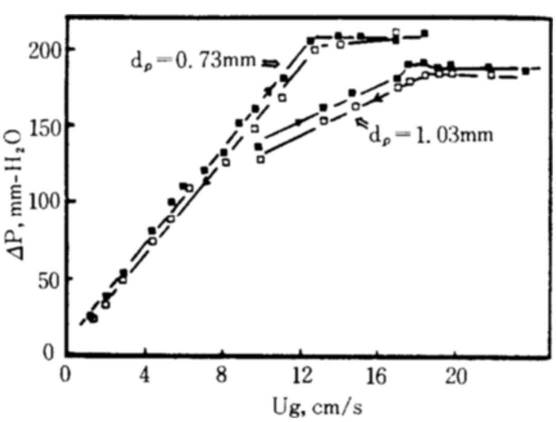

Fig. 1. Pressure drop vs. gas velocity for minimum fluidizing velocity determination.

RESULTS AND DISCUSSION

1. Minimum Fluidizing Velocity

The minimum fluidizing velocity of the coal particles have been determined from the plot of pressure drop versus air velocity as shown in Fig 1. As can be seen from the figure that the minimum fluidizing velocities are 12.6 cm/s and 20.6 cm/s for the mean particle sizes of 0.73 and 1.03 mm, respectively.

The obtained data were compared with the values from the correlation of minimum fluidizing velocity of Wen and Yu [14]. The values from the correlation [14] were 10.8 cm/s and 21.4 cm/s for the 0.73 and 1.03 mm coal particles, respectively. Thus the present experimental values of minimum fluidizing velocities are well accord with the values from the correlation.

2. Transition velocity between Bubbling and Turbulent Bed (Uk):

As the gas velocity is further rasied from minimum fluidizing velocity, the size of bubbles increases, which results in the extensive vertical acceleration and deceleration of the bed, and the hetrogeneous two phase character of bed begins to change toward a condition of increasing homogeneity until a point is reached at which large bubbles are on the whole absent, which marks the onset of the turbulent flow regime.

The transition from bubbling to turbulent is reflected in the fluctuations of both the dynamic pressure at any point in the bed and of the pressure drop across it. In that sense, it can be characterized by two velocities, namely the velocity at which pressure fluctuations begin to diminish from their peak value (Uc) and the velocity at which the pressure drop fluctuations having decayed from their peak value and begin to level off (Uk).

With this regard, the transition velocities, Uk, are found to be 103 and 130 cm/s for 0.73 and 1.03 mm particles, respectively (Fig. 2, 3) since the terminal velocity of larger particle has a higher value than that of smaller one.

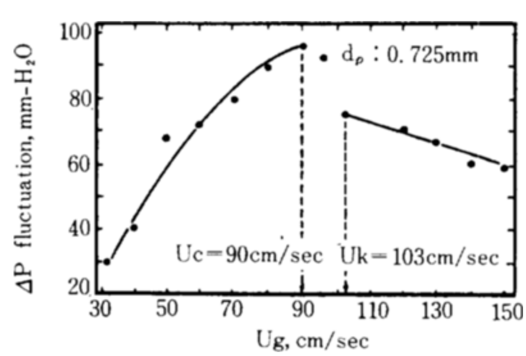

Fig. 2. Pressure fluctuation vs. gas velocity for determination of Uc and Uk.

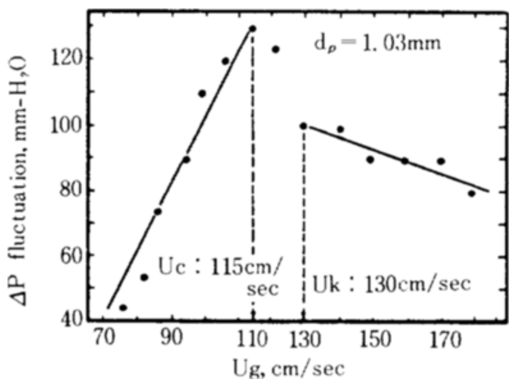

Fig. 3. Pressure fluctuation vs. gas velocity for determination of Uc and Uk.

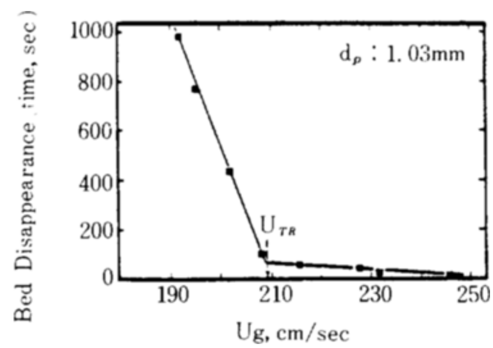

Fig. 5. Bed material disappearance time vs. gas velocity for determination of transport velocity.

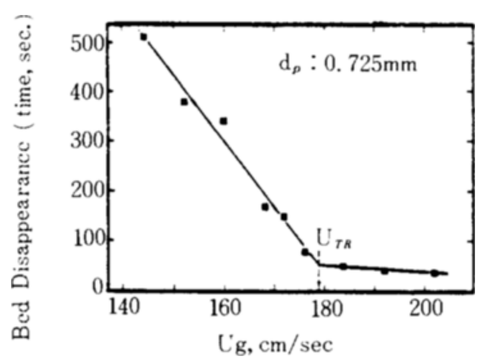

Fig. 4. Bed material disappearance time vs. gas velocity for determination of transport velocity.

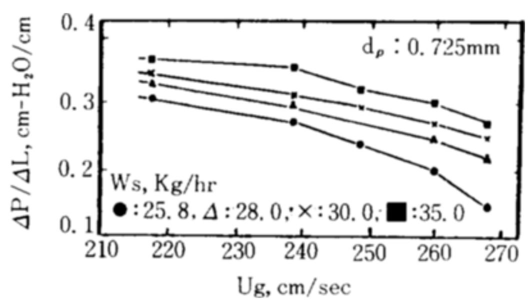

Fig. 6. Pressure gradient variation with gas velocity.

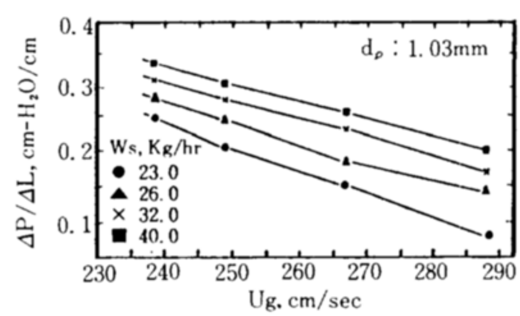

Fig. 7. Pressure gradient variation with gas velocity.

3. Transition Velocity between Turbulent and Fast Fluidized Bed (Utr)

As the gas velocity is further raised beyond the transition velocity from bubbling to turbulent beds, the particle carry over rates are comparatively high and the turbulent regime extends to the transport velocity, Utr, which marks the onset of cocurrent transport flow of gas and solids. The transport velocity has been determined by measuring the disappearance time it took the bed material to empty at a given gas velocity. In the present study, the disappearance time of solids is 3% of initial coal feeding remains in the bed which corresponds to pressure drop across the bed to decay 2.0 cm of water.

As can be seen from Fig. 4 and 5, the transport velocity, Utr can be determined from the kink point of the slopes since the entrainment of solids in a fluidized bed increases exponentially with gas velocity. The resulting values of Utr are 178 cm/s for 0.73 mm particle and 209 cm/s for 1.03 mm particle, respectively.

4. Fast Fluidized Beds

Beyond the transport velocity, solid traverses the bed in transport flow and the concentration of the suspended solids depends not only on gas velocity but also on the solid flow rate (Fig. 6-9). As can be seen from the figures that pressure drop decreased with gas velocity but increased with solid recycle rate since bed density decreased with gas velocity whereas the increase of solid

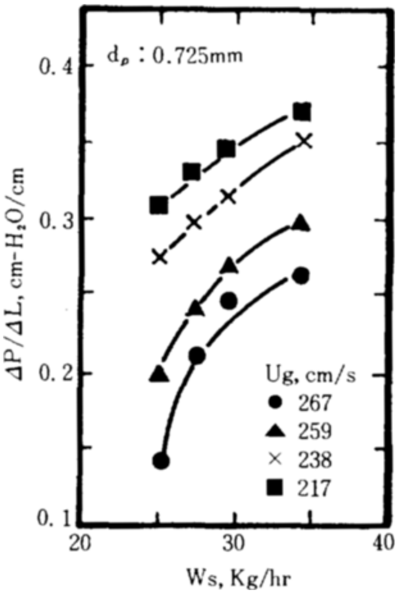

Fig. 8. Pressure gradient variation with solid recycle rate.

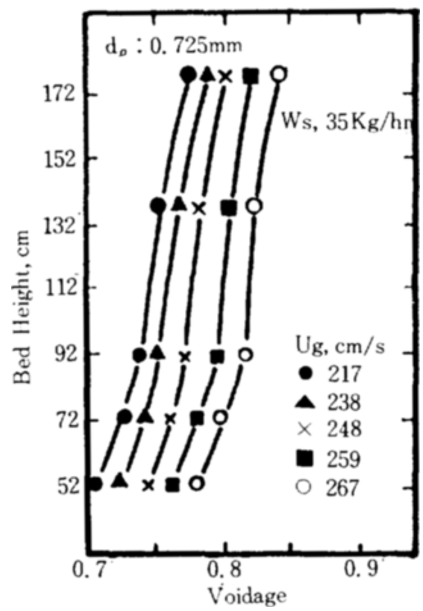

Fig. 10. Bed voidage distribution along the bed height.

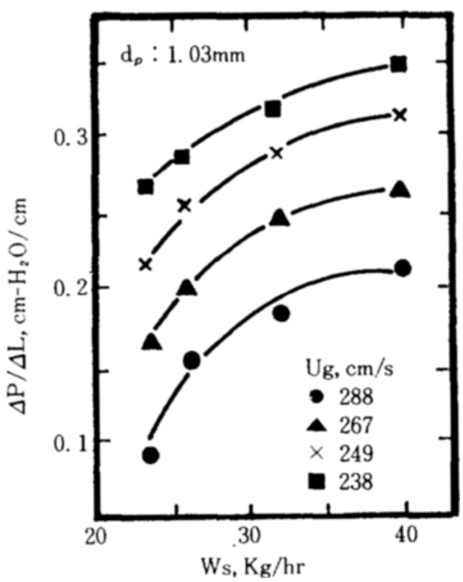

Fig. 9. Pressure gradient variation with solid recycle rate.

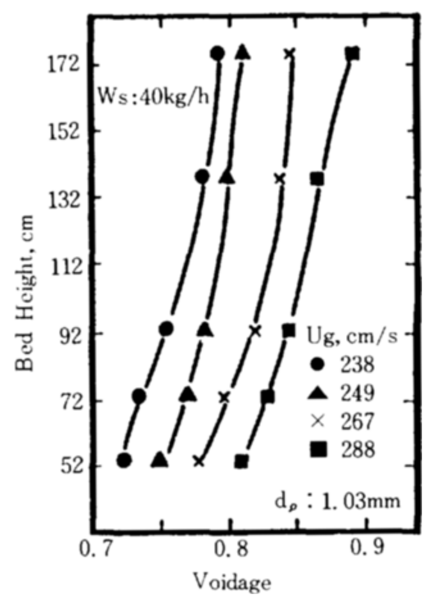

Fig. 11. Bed voidage distribution along the bed height.

recycle rate resulted in higher bed density at the given gas velocity. The pressure gradient somewhat decreased with recycle rate since the friction between wall and solid may decrease with the increase of dense phase concentration [3, 12].

The voidage variation in the bed with bed height at the given recycle rates can be seen in Fig. 10 and 11. The bed voidage has been calculated from the following relation since solid friction to be less than 10% of the total pressure drop in any section of the turbulent and fast fluidization regimes [1,11]. Thus it can be assumed that the overall pressure drop is equal to the weight of

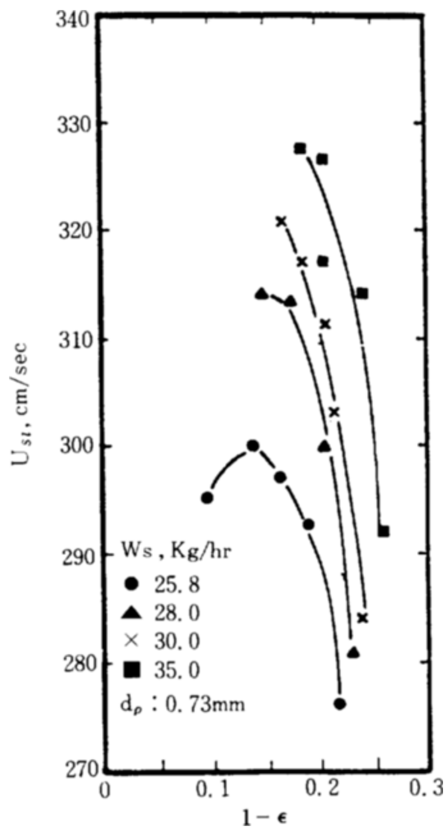

Fig. 12. Relationship between slip velocity and solid concentration.

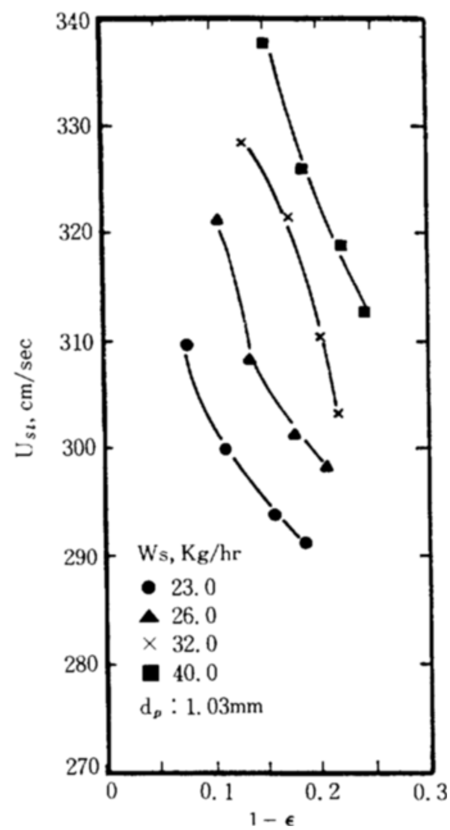

Fig. 13. Relationship between slip velocity and solid concentration.

solids in the bed:

$$\Delta P = \rho_s (1-\varepsilon)\ gL \tag{1}$$

As can be found in the figures that a slight decrease in solid fraction or increase of bed voidage with bed height and the bed voidage in the fast fluidized regime lies in the range of 0.75-0.95 [1,11]. Also, the bed voidage depends on both superficial gas velocity and solid recycle rate [8].

The bed voidage in the bed of larger particle (dp = 1.03 mm) is comparatively lower than that of smaller one since the carryover rate of smaller particle is higher than that of larger particle. Also, the voidage distribution in the bed of smaller particle is more uniform than the bed of larger particle because the degree of solid backmixing by the solids refluxing would be higher in the bed of smaller one than that of larger particle. Thus, it may suggest that the bed of smaller particle would give more uniform fast fluidization (Fig. 10 and 11).

Slip velocity, Usl, between the phases can be defined as the velocity difference between actual gas velocity through the bed of particles and the mean solid velocity (1) as shown:

$$Usl = Ug/\varepsilon - Us \tag{2}$$

in which Ug. ε and Us are the superficial air velocity, bed voidage and mean solid velocity, respectively. The mean solid velocity is defined as;

$$Us = Gs/\rho \tag{3}$$

where Gs is the solid rate per cross sectional area and ρ is the bed density.

The slip velocity decreased with solid concentration in the bed, $(1-\varepsilon)$, and it increased with solid recycle rate as can be seen in Fig. 12 and 13. Also, the slip velocity increased with superficial gas velocity. Since the slip velocity has been used as a degree of solid backmixing [13,15,16], the solid backmixing increased with increase of solid recycle rate, bed voidage and gas velocity.

In a transport of solid particles with fluid, the chocking velocity is an important parameter to determine the demarcation line between dilute and dense phases flow at the given solid feeding rate. It is well known that the prssure drop decreases initially with gas velocity but it

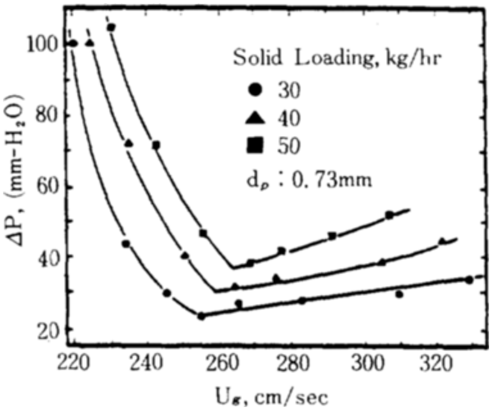

Fig. 14. Pressure drop vs. gas velocity for determination of chocking velocity.

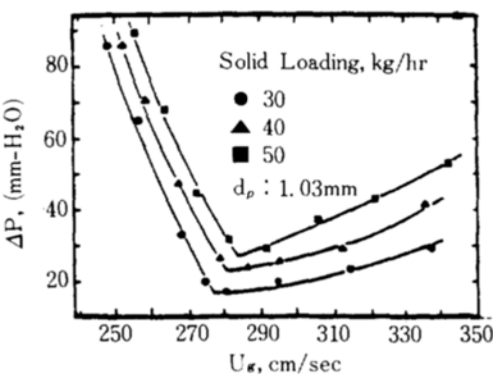

Fig. 15. Pressure drop vs. gas velocity for determination of chocking velocity.

again increases with further increase of gas velocity due to the increase of gas-wall and solid-wall frictions [7]. From the present experimental data, the chocking velocity increased with solid feeding rate at the given particle size. (Fig. 14, 15)

As can be seen from the figures that the chocking velocity for 0.73 and 1.03 mm particles lies in the range of 2.55-2.65 m/s and 2.77-2,84 m/s, respectively at the given solid feeding rates. These values are well accord to the correlation suggested by Leung et al. [7].

CORRELATIONS OF Uc AND Uk

The limited experimental data of the present and previous studies [5, 10, 11, 18] on Uk and Uc have been correlated with the experimental variables. The resulting correlations as follows;

$$Uc = 60.00 dp^{0.29} \rho_s^{0.58} D_t^{0.53} \tag{4}$$

with correlation coefficient of 0.93,

$$Uk = 45.24 dp^{0.18} \rho_s^{0.96} D_t^{0.52} \tag{5}$$

with correlation coefficient of 0.82.

These correlations cover the range of variables $0.0024 < dp < 0.26$ cm, $1.07 < \rho s < 2.92$ g/cm³, $7.79 < D_t < 30.5$ cm.

In summary, the minimum fluidizing velocity, transition velocity between bubbling to turbulent fluidizations the transition velocity between turbulent and fast fluidized beds and chocking velocity have been determined.

The data of Uc and Uk in the present and previous studies have been correlated with the experimental variables. In general, the Uc and Uk increased with particle size, solid density and column diameter.

NOMENCLATURE

dp : particle diameter, cm
Dt : column diameter, cm
Gs : solid rate, Kg/s/m²
L : bed height, cm
ΔP : pressure drop, gr/cm²
Uc : the velocity at which the pressure fluctuations in a bubbling bed begin to diminish from their peak value, cm/s
Ug : superficial gas velocity, cm/s
Uk : the velocity at which the turbulent fluidized bed begins, cm/s
Us : mean solid velocity, cm/s
Usl : slip velocity of solid, cm/s
Utr : transport velocity, cm/s
Ws : solid recycle rate, Kg/hr.
ρ : bed density, gr/cm³
ρ_s : particle density, gr/cm³
ε : gas voidage

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