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Effects of Operating Variables on the Solid Circulation Rate in a Three-phase Circulating Fluidized Bed

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Abstract – Effects of operating variables on the solid circulation rate were investigated in a three-phase circulating fluidized bed, of which inside diameter was 0.102m and height was 3.5m, respectively. Gas velocity, primary and secondary liquid velocities, particle size and height of solid particles piled up in the solid recycle device were chosen as operating variables. The solid circulation rate increased with increasing primary and secondary liquid velocities and height of solid particles piled up in the solid recycle device, but decreased with increasing particle size. The value of solid circulation rate decreased only slightly with increasing gas velocity in the riser. The values of solid circulation rate were well correlated in terms of dimensionless groups within the experimental conditions.

Key words: Three Phase, Circulating Fluidized Bed, Solid Circulation Rate

1. Introduction

Three-phase circulating fluidized beds can be utilized as a reactor or a contactor in the fields of petrochemical, biochemical, food, metallurgical and medical engineering due to their highly unique features and advantages such as effective contacting among gas, liquid and solid phases, minimizing the dead zone interior of the flow system, continuous regeneration of deactivated catalyst, adsorbent or absorption media, increase in the fractional conversion as well as production efficiency [1-5]. Several investigators, therefore, have studied three-phase circulating fluidized beds. Individual phase holdup, liquid dispersion and mixing, flow regime, bubble properties, heat and mass transfer coefficients have been investigated to understand the system, in order to employ it in various kinds of industries [6-12]. However, most of the previous studies have their attention on the phenomena in the riser without any consideration on the control of solid circulation rate, which is one of the important factors in determining the characteristics and performance of three-phase circulating fluidized beds. Thus, in the present study, characteristics of solid circulation rate were studied in the three-phase circulating fluidized bed system. Effects of operating variables such as primary and secondary liquid velocities, gas velocity, particle size and height of solid particles piled up in the solid recycle device(downcomer) on the solid circulation rate were examined.

2. Experiments

Experiments were carried out in a three-phase circulating fluidized bed made of acrylic columns. The system was composed of three main sections: the riser, gas-liquid-solid separator, and solid recycle device, as can be seen in Fig. 1. The details of experimental apparatus can be seen elsewhere [10-13]. The diameter and height of the riser were 0.102 m and 3.5 m, respectively. A stainless steel perforated plate installed at the bottom of the riser was used as the gas and primary liquid distributor. A 0.2 m high stainless steel column was used as the distributor box into which water was introduced through a 0.025 m pipe from the liquid reservoir. Oil-free compressed air was fed to the riser through a pressure regulator, filter, and a calibrated gas flow meter. The gas was admitted to the riser through four 3.0 mm ID perforated pipes drilled horizontally in the grid of the gas and liquid distributor. The pipes were evenly spaced across the grid having 12 holes, of which diameters were 1.0 mm. The solid particles which were separated at the top of the riser were returned to the bottom of it through the solid recycle device. The solid particles were circulated by adjusting the gas velocity, primary and secondary liquid velocities, height of the solid particles piled up in the solid recycle device. Glass beads of density 2500 kg/m^3 were used as the fluidized solid particle. The particle diameter was either 0.5, 1.0, 2.0 or 3.0×10^{-3}m. The solid circulation rate (G_S), which was measured at least three times, was determined by measuring the amounts of particles piled up above the butterfly valve in the solid recycle device [10-15] in a given steady state condition. The measured values of G_S agreed well with each other within 3~4% deviations. Tap water, of which density and surface tension were 1000 kg/m^3 and 72.75×10^{-3}N/m, respectively, was used as a continuous liquid phase. The pressure taps for measuring pressure fluctuations were located at 0.5 m above the solid recycle port in the riser and above the distributor in the solid recycle device, respectively. Each pressure tap interval was 0.2 m. The pressure transducer produced an output voltage proportional to the pressure fluctuation signal. The signal was processed by a data acquisition system (Data

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‡This article is dedicated to Prof. Seong-Youl Bae on the occasion of his retirement from Hanyang University.

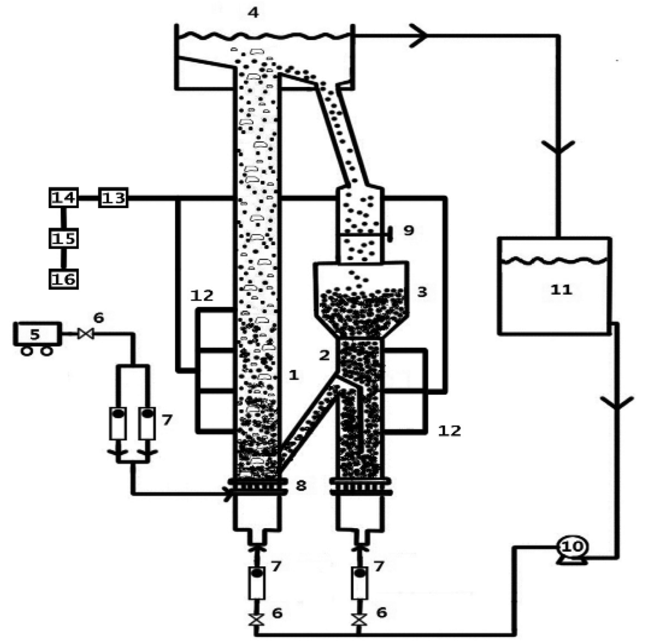

Fig. 1. Schematic diagram of a three-phase circulating fluidized bed.

1. Riser	9. Butterfly valve
2. Down comer	10. Pump
3. Hopper	11. Liquid reservoir
4. L/S separator	12. Pressure tap
5. Compressor	13. Pressure sensor
6. Control valve	14. Data acquisition system
7. Flowmeter	15. A/D converter
8. G/L distributor	16. Computer

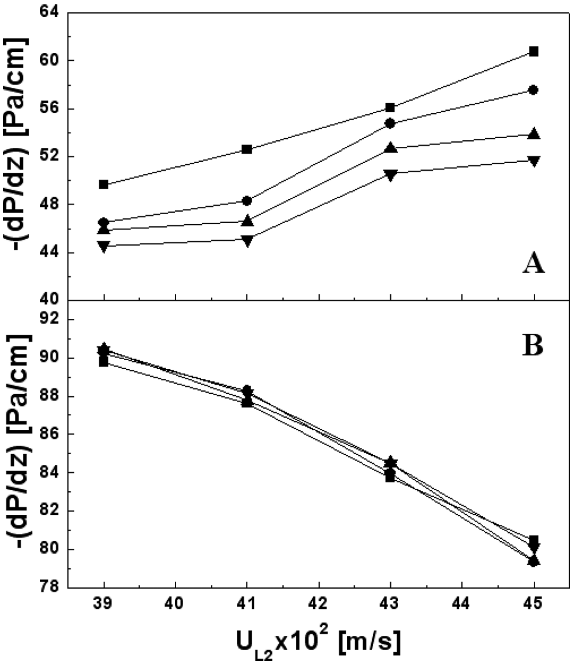

Fig. 2. (A) Effects of secondary liquid velocity on the axial pressure gradient in the riser column (d_P : 0.003 m, U_{L1} : 0.39 m/s, h : 1.2 m), (B) Effects of secondary liquid velocity on the axial pressure gradient in the solid recycle device. (d_P : 0.003 m, U_{L1} : 0.39 m/s, h : 1.2 m).

		■	●	▲	▼
(A)	$U_G \times 10^2$ [m/s]:	1.0	3.0	5.0	7.0
(B)	$U_G \times 10^2$ [m/s]:	1.0	3.0	5.0	7.0

Precision Model, D-6000) and a personal computer. The voltage-time signals, corresponding to the pressure-time signals, were sampled at a rate of 0.01 s and stored in the data acquisition system. The total data acquisition time was 10 s, thereby yielding a total of 1000 data points to analyze sufficiently the characteristics of pressure fluctuations in each experimental condition. The signals were transferred to the computer and processed off-line.

3. Results and Discussion

Effects of secondary liquid velocity (U_{L2}) on the axial pressure gradients (-dP/dz) in the riser column and solid recycle device can be seen in Fig. 2, where the value of the pressure gradient increases with increasing secondary liquid velocity in both column. The increase of U_{L2} can lead to increase the amount of solid input to the riser column from the solid recycle device; thus, the solid holdup could increase in the riser column, which consequently results in an increase of the axial pressure gradient. However, the increase of U_G in the riser column leads to the decrease in the pressure gradient, due to the increase in the gas holdup in the riser (Fig. 2A). In the solid recycle device, the increase of U_{L2} can expand the particle bed; thus, the values of -(dP/dz) decrease with increasing U_{L2}. The value of U_G in the riser column, of course, does not affect the axial pressure gradient in the solid recycle device (Fig. 2B).

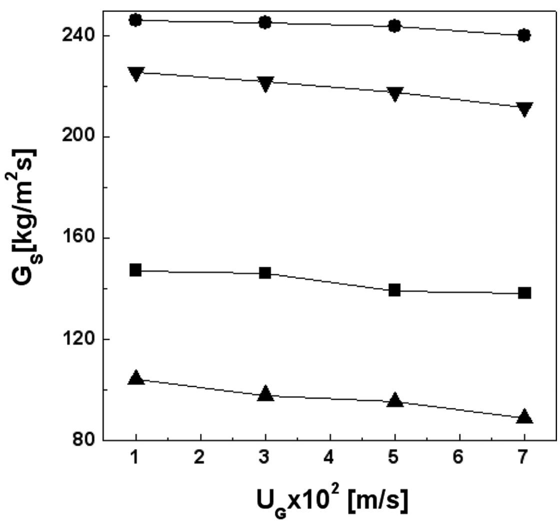

Fig. 3. Effects of gas velocity on the solid circulation rate.

	■	●	▲	▼
$d_p \times 10^3$ [m]:	0.5	0.5	1.0	1.0
$U_{L1} \times 10^2$ [m/s]:	39.0	39.0	41.0	41.0
$U_{L2} \times 10^2$ [m/s]:	4.0	6.0	6.0	8.0
h × 10^2 [m]:	120.0	140.0	140.0	160.0

Effects of gas velocity in the riser on the solid circulation rate (G_S) can be seen in Fig. 3, where the value of G_S decreases only slightly, although the turbulence among gas, liquid, and solid phases is observed

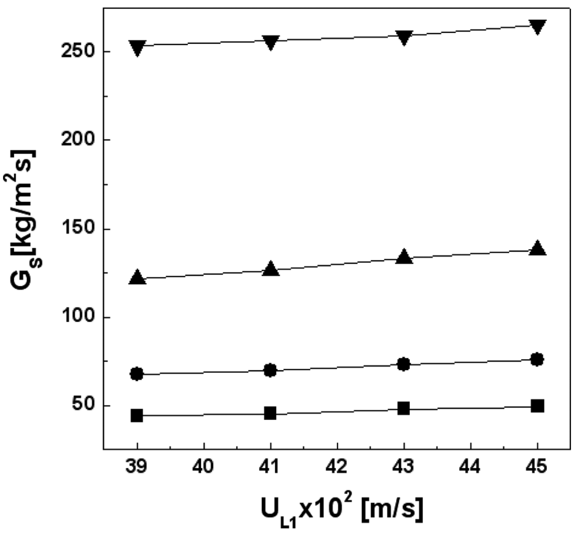

Fig. 4. Effects of primary liquid velocity on the solid circulation rate.

	■	●	▲	▼
$d_p \times 10^3$ [m]:	1.0	1.0	1.0	0.5
$U_G \times 10^2$ [m/s]:	1.0	3.0	5.0	5.0
$U_{L2} \times 10^2$ [m/s]:	4.0	6.0	8.0	8.0
$h \times 10^2$ [m]:	120.0	120.0	140.0	140.0

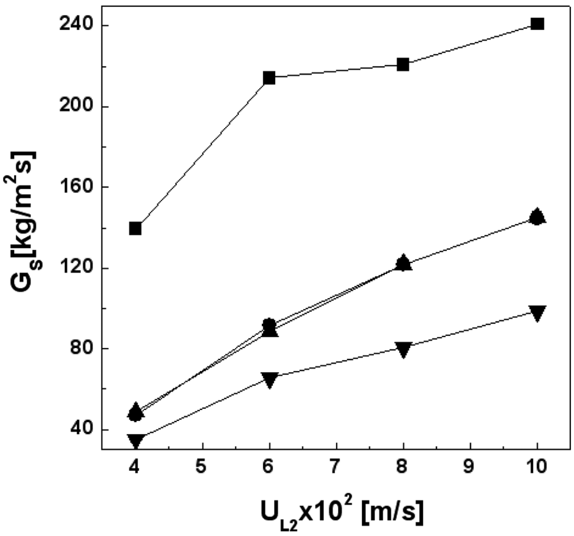

Fig. 5. Effects of secondary liquid velocity on the solid circulation rate.

	■	●	▲	▼
$d_p \times 10^3$ [m]:	0.5	1.0	1.0	2.0
$U_G \times 10^2$ [m/s]:	5.0	5.0	7.0	7.0
$U_{L1} \times 10^2$ [m/s]:	39.0	39.0	41.0	41.0
$h \times 10^2$ [m]:	120.0	140.0	140.0	160.0

to increase noticeably with increasing gas velocity. This can be because the range of gas velocity is much lower than that of liquid velocity, since it has not been required to increase the gas velocity to maintain the relatively high level of contacting efficiency between gas and liquid phases. In addition, the density of gas is much lower than that of liquid phase, which leads to negligible effects on the drag force acting on the rising particles in the riser. Therefore, the value of solid circulation rate does not change considerably with varying gas velocity.

Effects of primary liquid velocity (U_{L1}), which is the liquid velocity introduced into the riser through the liquid distributor, on the solid circulation rate can be seen in Fig. 4. In Fig. 4, the value of G_S increases only slightly with increasing U_{L1}. The drag force acting on the particles increases with increasing primary liquid velocity, which leads to an increase of rising velocity of solid particles slightly in the riser column; therefore, the value of G_S increases slightly with increasing primary liquid velocity. However, the effect of primary liquid velocity in the riser on the solid circulation rate is not significant.

The effect of secondary liquid velocity (U_{L2}), which is defined as the flux of liquid introduced into the riser through the solid recycle device with solid particles, on the solid circulation rate can be seen in Fig. 5. The value of G_S increases with increasing secondary liquid velocity. This is ascribed to that the amount of solid particles recycled into the riser increasing with increasing U_{L2}. Note that the liquid velocity in the riser was determined by summation of the primary and secondary liquid amount introduced into the riser; thus, the solid circulation rate can be adjusted in a given liquid velocity in the riser.

The effect of particle size on the solid circulation rate can be seen in Fig. 6, where the value of G_S decreases with increasing solid particle

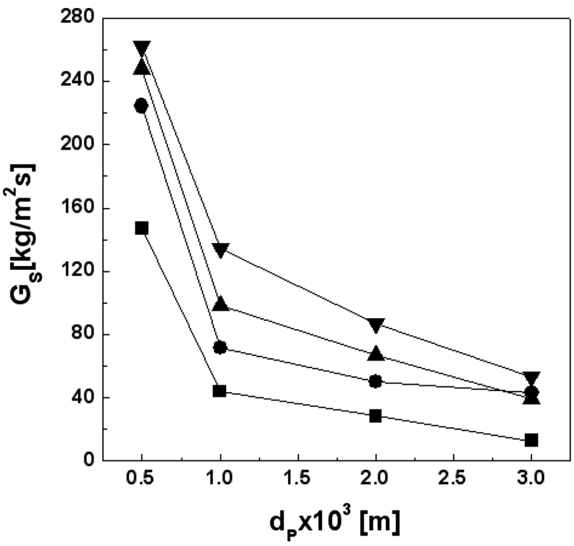

Fig. 6. Effects of particle size on the solid circulation rate.

	■	●	▲	▼
$U_G \times 10^2$ [m/s]:	1.0	1.0	3.0	3.0
$U_{L1} \times 10^2$ [m/s]:	39.0	41.0	41.0	43.0
$U_{L2} \times 10^2$ [m/s]:	4.0	6.0	6.0	8.0
$h \times 10^2$ [m]:	120.0	120.0	140.0	140.0

size. Since the terminal velocity of particles increases with increasing particle size, the amount of particles entrained from the top of the riser could decrease with increasing particle size, which results in the decrease of solid circulation rate with increasing particle size. This means that the solid holdup in the riser could increase with increasing particle size [16-21].

The effect of the height of solid particles piled up in the solid recycle

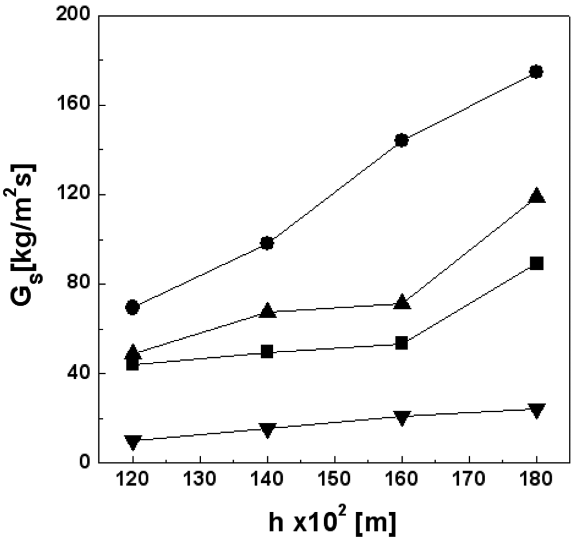

Fig. 7. Effects of height of solid particles piled up in the solid recycle device on the solid circulation rate.

	■	●	▲	▼
$d_p \times 10^3$ [m]:	1.0	1.0	2.0	3.0
$U_G \times 10^2$ [m/s]:	1.0	3.0	3.0	1.0
$U_{L1} \times 10^2$ [m/s]:	39.0	41.0	41.0	39.0
$U_{L2} \times 10^2$ [m/s]:	4.0	6.0	6.0	4.0

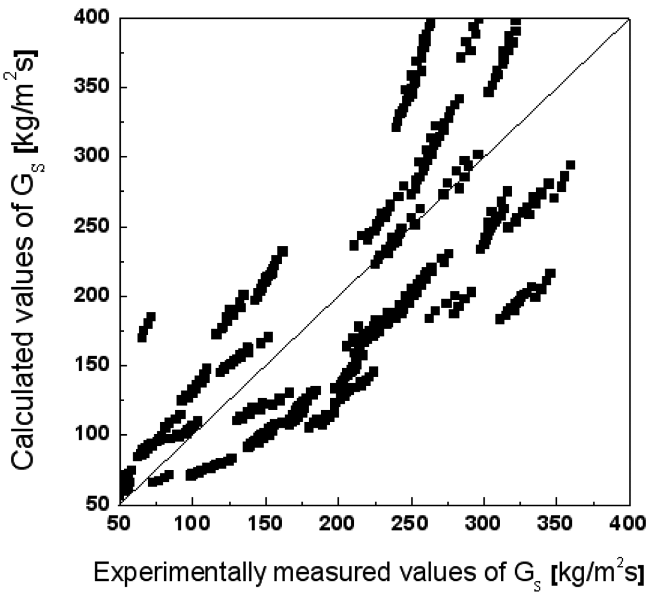

Fig. 8. Comparison between the measured and the calculated values of G_S.

device (downcomer) on the solid circulation rate can be seen Fig. 7, where the value of G_S increases with increasing the height. This is ascribed to the fact that the amount of solid particles flowing downward due to gravitational force could increase with increasing the height of solid particles stored in the hoper.

The values of solid circulation rate were well correlated in terms of dimensionless groups as Eq. (1). As can be seen in Fig. 8, it is well fitted with experimentally measured values with a correlation coefficient of 0.923.

$$\frac{G_S}{U_G\rho_L} = 0.00837\left[\frac{d_P(U_{L1}+U_{L2})\rho_L}{\mu_L}\right]^{0.266}\left[\frac{d_P}{h}\right]^{-0.487} \quad (1)$$

4. Conclusion

Characteristics of solid circulation rate were successfully analyzed by considering the effects of operation variables. The value of solid circulation rate did not change considerably with variations of gas and primary liquid velocities in the riser column. The value of solid circulation rate increased with increasing secondary liquid velocity and the height of solid particles piled up in the solid recycle device, but decreased with increasing particle size. The value of solid circulation rate was well correlated in terms of dimensionless groups, which could be utilized to adjust the solid circulation rate in three-phase circulating fluidized bed systems.

Nomenclatures

- $-(dP/dz)$: axial pressure gradient [Pa/cm]
- G_S : particle circulation rate [kg/m^2·s]
- U_G : superficial gas velocity [m/s]
- U_{L1} : primary superficial liquid velocity [m/s]
- U_{L2} : secondary superficial liquid velocity [m/s]
- h : height of solid particles piled up in the solid recycle device [m]
- H : bed height [m]
- d_P : particle diameter [mm]
- μ_L : liquid viscosity [Pa·s]
- ρ_L : liquid density [kg/m^3]

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