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Solid Circulation Rate in a 3-phase (gas/liquid/solid) Viscous Circulating Fluidized Bed

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Abstract – For the first time, the characteristics of solid circulation rate (G_S) were investigated in a three-phase (gas-liquid-solid) viscous circulating fluidized bed (TPCFB). The solid circulation rate was controlled separately by adjusting the experimental apparatus as well as operating variables. Effects of primary and secondary liquid velocities (U_{L1} and U_{L2}), gas velocity (U_G), particle size (d_p), height of particles piled up in the solid recycle device (h), and viscosity of continuous liquid media (μ_L) on the value of G_S were determined. The experimental results showed that the value of G_S increased with increases in the values of U_{L1}, U_{L2}, h and μ_L, while it decreased with increasing U_G and d_p in TPCFBs with viscous liquid media. The values of G_S were well correlated in terms of dimensionless groups within this experimental conditions.

Key words: Solid circulation rate, Three phase, Circulating fluidized bed, Viscous liquid

1. Introduction

Taking advantage of three-phase fluidized beds (TPFB), the three-phase circulating fluidized bed (TPCFB) has been developed by employing the circulation mode of fluidized solid particles. The circulation of particles enables the TPCFB to overcome the restrictions of conventional TPFB related to the limited liquid velocity, since the liquid velocity has to be adjusted between the minimum and the terminal velocities of particles in various kinds of continuous liquid media [1-6]. In addition, the dead zone can be minimized, the contacting efficiency among multiphase can be increased, the continuous processing and regeneration of deactivated catalysts and solid media can be possible and the effective removal or supply of heat as required can be realized effectively in TPCFBs [6-11]. Numerous investigations have been conducted, therefore, to analyze and apply the TPCFB in the diverse fields of petrochemical, environmental, food, biochemical, energy and medical engineering [3-10].

The characteristics of TPCFB were measured and analyzed by several methods [10-18]. The unique features of TPCFB come from the circulation mode of fluidized particles under the condition of high U_L range in TPCFB. The circulation mode has been reported by two kinds of schemes; one is a separately controlled scheme, and the other is the scheme of particle circulation without control. In the former system, the circulation rate of particles is controlled by means of recycle device by adjusting the secondary liquid flow rate, valve opening, guide angle and height of particles piled up in the downer [9,10,15,19-23]. However, in the latter system, the particle circulation rate could not be controlled.

Since the particle circulation rate is one of critical parameters in TPCFB, some investigators have studied it and reported the correlations to predict the particle circulation rate [4,22,24]. For the practical applications of TPCFB, information on the particle circulation rate in various kinds of conditions has been required. Especially, it has been frequently encountered that the liquid phase can be viscous. No doubt, the hydrodynamics and heat and mass transfer phenomena could be quite different in the viscous liquid medium from those in the water [19,20,22-24]. However, there has been little information on the particle circulation rate in the TPCFB, especially in a bed with viscous liquid medium. Thus, in the present study, the particle circulation rate was measured and its characteristics were discussed in TPCFB with viscous liquid medium.

2. Experiment

Experiments were carried out in the riser of TPCFB of which diameter and height were 0.102 m and 2.40 m, respectively. The TPCFB was composed of three main sections; the riser column, gas-liquid-solid separator and solid recycle device, as can be seen in Fig. 1. The details of experimental apparatus can be found elsewhere [21-23]. Glass beads, of which diameter was in the range of 0.5~3.0×10^{-3} m (ρ_s=2500 kg/m^3), were used as fluidized solid particles, and aqueous solutions of carboxymethyl-cellulose (CMC) as liquid phase, respectively. Filtered and compressed air was used as the gas phase, which was admitted to the riser through the gas distributor located at the bottom of the riser. The apparent viscosity of liquid media, which was measured by viscometer (Brookfield LVD II Viscometer), was in the range of 1.0~28.0×10^{-3} Pa·s. The circulation rate of solid particles, which were recycled to the bottom of the riser through the solid recy-

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‡This article is dedicated to Prof. Jea Keun Lee on the occasion of his retirement from Pukyung National University.

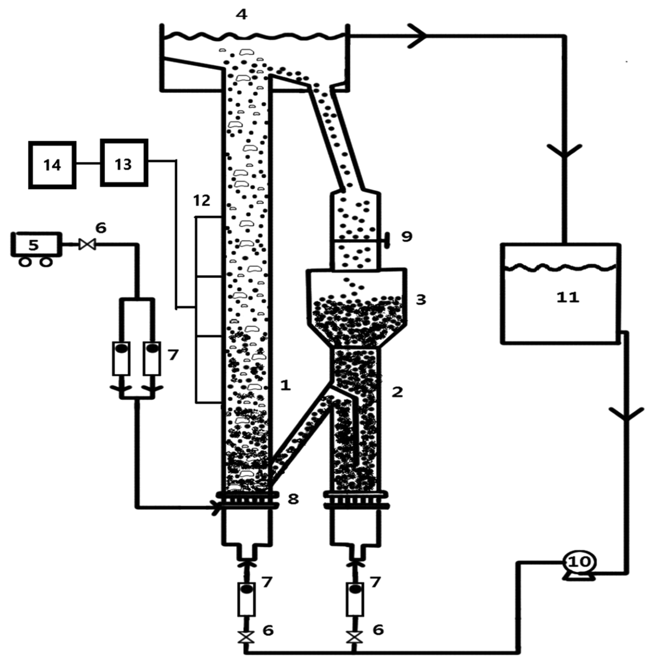

Fig. 1. Schematic diagram of experimental apparatus.

1. Riser	8. G/L distributor
2. Downer	9. Butterfly valve
3. Hopper	10. Liquid pump
4. G/L/S separator	11. Liquid reservoir
5. Compressor	12. Pressure tap
6. Control valve	13. A/D converter
7. Flowmeter	14. Computer

cle device, was determined by measuring the amount of solid particles piled up above the butterfly valve in the solid recycle device [9,10,19-23]. The solid circulation rate was adjusted by varying the secondary liquid flow rate (U_{L2}) and the height of particles piled up in the recycle device (h) with fixed angle and length of guide. The solid particles were recycled by means of solid recycle device from the bottom of the riser with a given value of G_S.

3. Results and Discussion

Effects of primary liquid velocity (U_{L1}) on the particle circulation rate (G_S) can be seen in Fig. 2. In this figure, the value of G_S increases gradually with increasing U_{L1}. This can be due to the increase of upward drag force acting on the particles with increasing U_{L1} [4-6]. That is, the rising velocity of particles in the riser could increase with increasing U_{L1}, thus, the circulation rate of particles into the riser could increase as well. Effects of secondary liquid velocity (U_{L2}) on the G_S value can be seen in Fig. 3, where the value of G_S increases with increasing U_{L2}. The secondary liquid is fed to the bottom of the downer in order to control the G_S in given conditions of angle and length of guide, as can be seen in Fig. 1. The increase of U_{L2} can increase the force to fluidize the particles at the bottom of the downer, and thus to increase the amount of particles fed into the bottom of the riser, which consequently results in the increase of G_S in the riser [19-22].

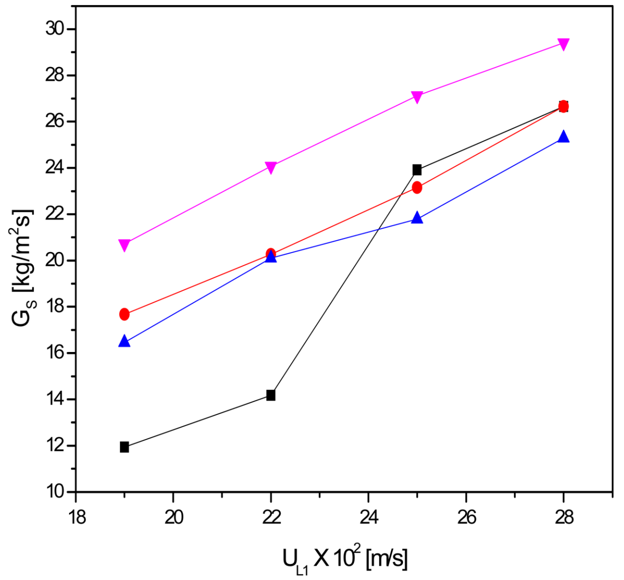

Fig. 2. Effects of U_{L1} on the G_S in TPCFBs with viscous liquid medium.

	■	●	▲	▼
$\mu_L \times 10^3$ [Pa·s]	13.4	18	24	24
$d_p \times 10^3$ [m]	3	1	2	2
$h \times 10^2$ [m]	150	150	130	170
$U_{L2} \times 10^2$ [m/s]	4	1	2	3
$U_G \times 10^2$ [m/s]	1	1	2	1

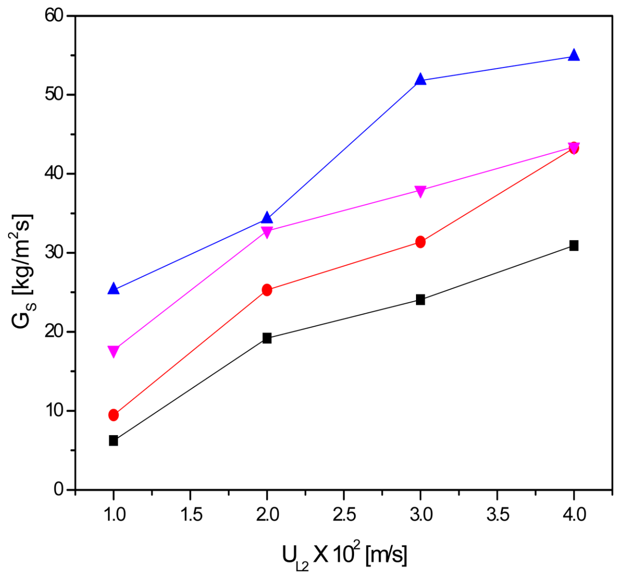

Fig. 3. Effects of U_{L2} on the G_S in TPCFBs with viscous liquid medium.

	■	●	▲	▼
$\mu_L \times 10^3$ [Pa·s]	18	24	24	13.4
$d_p \times 10^3$ [m]	2	2	1	1
$h \times 10^2$ [m]	170	130	130	150
$U_{L1} \times 10^2$ [m/s]	22	28	22	19
$U_G \times 10^2$ [m/s]	1	2	1	1

Effects of U_G on the G_S in a viscous TPCFB can be seen in Fig. 4, where G_S decreased with increasing U_G. The G_S is defined as the weight of particles per unit cross sectional area of the riser per unit time, but the upward drag force to fluidize the particles in the riser would decrease with increasing U_G. Thus, the value of G_S decreased with increasing U_G. It has been understood that the upward force act-

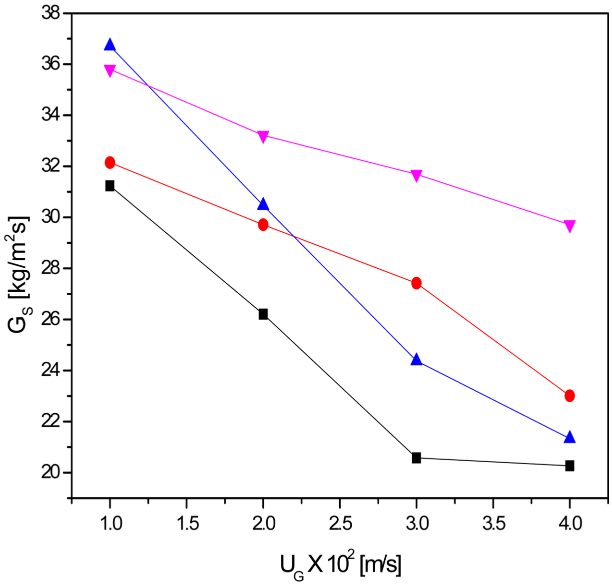

Fig. 4. Effects of U_G on the G_S in TPCFBs with viscous liquid medium.

	■	●	▲	▼
$\mu_L \times 10^3$ [Pa·s]	13.4	18	18	13.4
$d_p \times 10^3$ [m]	1	1	2	1
$h \times 10^2$ [m]	150	170	130	150
$U_{L1} \times 10^2$ [m/s]	22	19	25	19
$U_{L2} \times 10^2$ [m/s]	1	1	3	2

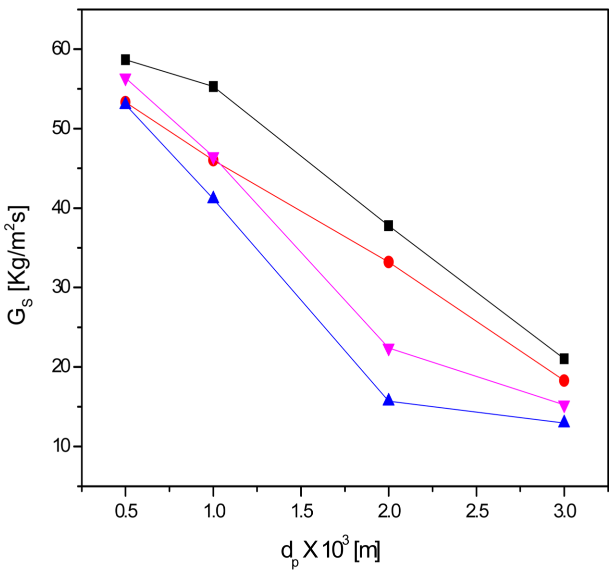

Fig. 5. Effects of d_p on the G_S in TPCFBs with viscous liquid medium.

	■	●	▲	▼
$\mu_L \times 10^3$ [Pa·s]	13.4	13.4	18	18
$h \times 10^2$ [m]	170	150	150	150
$U_{L1} \times 10^2$ [m/s]	25	25	22	25
$U_{L2} \times 10^2$ [m/s]	3	3	2	2
$U_G \times 10^2$ [m/s]	1	1	1	1

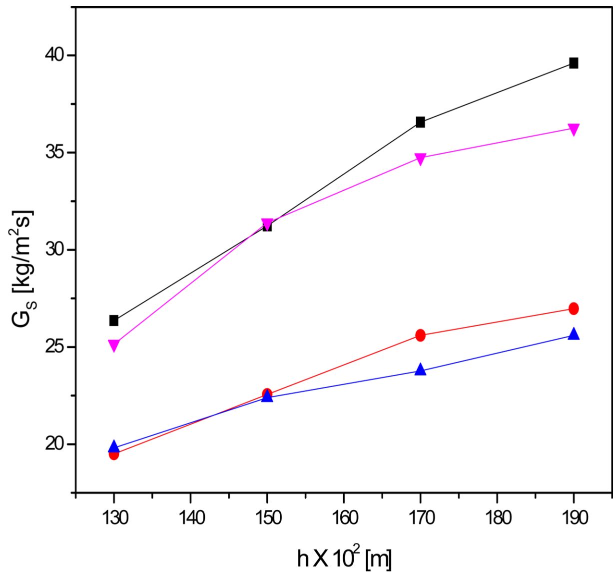

Fig. 6. Effects of h on the G_S in TPCFBs with viscous liquid medium.

	■	●	▲	▼
$\mu_L \times 10^3$ [Pa·s]	13.4	18	18	24
$d_p \times 10^3$ [m]	1	2	2	3
$U_{L1} \times 10^2$ [m/s]	22	22	25	22
$U_{L2} \times 10^2$ [m/s]	1	2	2	4
$U_G \times 10^2$ [m/s]	1	2	1	3

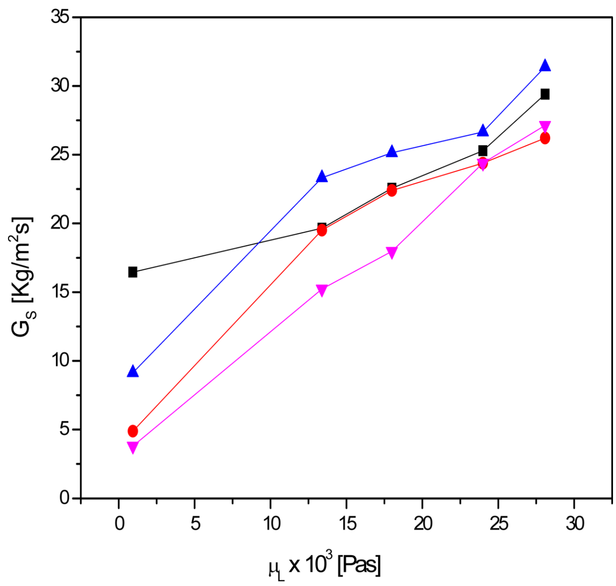

Fig. 7. Effects of μ_L on the G_S in TPCFBs with viscous liquid medium.

	■	●	▲	▼
$d_p \times 10^3$ [Pa·s]	1	2	2	3
$h \times 10^2$ [m]	130	150	150	170
$U_{L1} \times 10^2$ [m/s]	22	28	25	19
$U_{L2} \times 10^2$ [m/s]	1	2	3	4
$U_G \times 10^2$ [m/s]	1	2	1	1

ing on the particles could decrease with increasing gas holdup in the riser, because the density of gas is quite low comparing with that of continuous liquid media [7-13].

Effects of particle size on the value of G_S in a viscous TPCFB can be seen in Fig. 5, where the value of G_S decreased with increasing d_p. Since the downward force acting on the fluidized solid particles would increase with increasing d_p owing to the increase of weight, the upward velocity of particles could decrease with increasing d_p in a given fluidized condition. This could lead to the decrease of G_S with increasing d_p in the riser of the TPCFB [3,4,22]. Effects of height of particles piled up in the recycle device on the G_S can be seen in Fig. 6, where the value of G_S increased with increasing h. The increase of h means the increase of amount of particles piled up in the recycle device, which could lead to the increase of downward force of particles in the recycle device, which consequently results in the increase of particle amount moving downward in the recycle device and thus increase of particle amount injected into the riser of TPCFB in a given operational condition. Therefore, the value of G_S increased with increasing h in the particle recycle device.

Effects of liquid viscosity on the G_S in a viscous TPCFB can be seen in Fig. 7. The value of G_S increased gradually with increasing μ_L from 1.0 up to 28.0×10^{-3} Pa·s. This can be due to the increase of upward force acting on the fluidized particles with increasing μ_L. That is, the increase of viscosity of continuous liquid media could lead to the increase of viscous force at the particle surface contacting with the upward flowing liquid phase, which results in the increase of particle upward force and thus velocity in the riser. Therefore, the value of G_S increased with increasing μ_L in a viscous TPCFB [4,22,24].

The effects of operating variables on the value of G_S can be expressed by means of correlation of dimensionless groups. Since the solid circulation rate is closely related to the velocity of solid particles in the riser, the value of G_S can be included in the velocity ratio of liquid and particles in the riser, U_L/U_S, to compare their velocities. The velocity ratio of liquid and particles was well correlated in terms of the Reynolds number of particles in the viscous liquid flow including the primary and secondary flow rates and the ratio of particle size to the height of particles piled up in the solid recycle device, h/d_p, as Eq. (1).

$$\frac{U_L}{U_S} = \frac{U_L}{G_S/\rho_S} = 42.78\left[\frac{d_p(U_{L1}+U_{L2})\rho_L}{\mu_L}\right]^{0.35}\left(\frac{d_p}{h}\right)^{0.24} \quad (1)$$

The correlation is well fitted to the experimental results with a correlation coefficient of 0.912, as can be seen in Fig. 8.

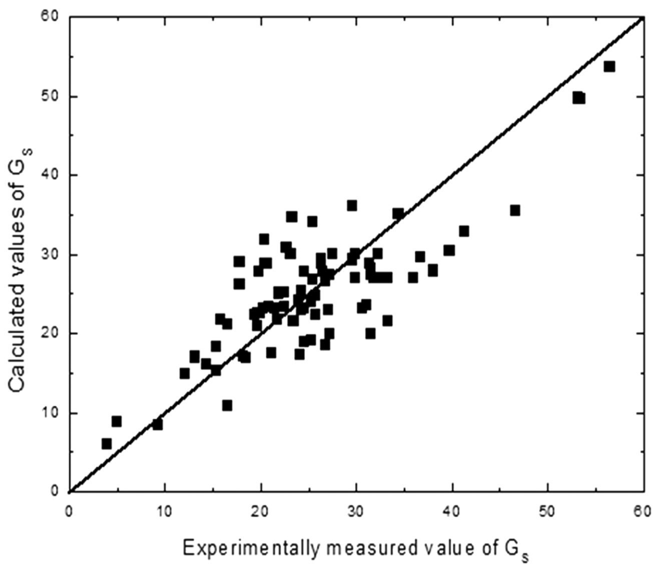

Fig. 8. Correlation to predict the G_S value.

4. Conclusion

For the first time, the solid circulation rate, which is a unique parameter in the circulating fluidized beds, was determined successfully in a three-phase (gas-liquid-solid) circulating fluidized bed with viscous liquid media. Effects of operating variables, such as U_{L1}, U_{L2}, U_G, d_p, h and μ_L on the value of G_S were determined by analyzing the highly complex and irregular behaviors of gas, liquid and solid particles with external circulation mode. The solid circulation rate was controlled by adjusting the experimental apparatus of solid recycle device such as guide angle and length as well as operating variables in order to consider the value of G_S as one of operating variables. The value of G_S increased with increasing U_{L1}, U_{L2}, h and μ_L, but decreased with increasing U_G, and d_p, in TPCFBs with viscous liquid media.

Nomenclature

d_p	: particle diameter [m]
G_S	: solid circulation rate [kg/m^2·s]
h	: height of particles [m]
U_G	: gas velocity [m/s]
U_{L1}	: primary liquid velocity [m/s]
U_{L2}	: secondary liquid velocity [m/s]
U_L	: total superficial liquid velocity [m/s]
U_S	: solid velocity [m/s]
μ_L	: liquid viscosity [Pa·s]
ρ_L	: liquid density [kg/m^3]
ρ_S	: solid density [kg/m^3]

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