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Hydrodynamic Characteristics of Air-Lift Activated Carbon Slurry Column with External Looping

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Abstract–The hydrodynamic characteristics of an air-lift activated carbon slurry column with external looping were investigated to find the optimal operating conditions of the slurry adsorption process that is frequently used as wastewater treatment, biological air pollutant removal and other environmental treatments. The experiments were conducted at different concentrations of adsorbents and gas inputs in the air-lift bubble column having external looping as batchwise contactor. The hydrodynamic behaviors were estimated with the residence time tracing of slurry adsorbents and gas holdups. The mixing characteristics were analyzed to find the best operating condition of an air-lift bubble column for the adsorbing equipment, and the performance of column was compared with that of internal looping.

Key words : Activated Carbon, External Looping, Residence Time

INTRODUCTION

An air-lift slurry bubble column is frequently used in environmental and chemical processes that require fluidization of phases for efficient heat and mass transport or homogenization. This system has an especially high ability to suspend fine particles due to the fast and stable slurry flow induced by the drafting path flow in the system [Swart, 1995].

Adsorption by activated carbon has been widely used in deodorization, recovery of materials and biological wastewater treatment [Chun, 1985; Colella, 1998; Han, 1985; Kim, 1990; Lee, 1988]. The active contact between adsorbents and adsorbate is a prerequisite condition for high efficiency of the liquid-solid adsorption process [Shrotri, 1998; Kolb et al., 1996]. Therefore, the air-lift slurry bubble column can be very adequately applied to the liquid phase adsorption contactor with powdered activated carbons. However, there is little systematic study of the equipment used for adsorbers in reactor design. Therefore, to investigate the optimal operating conditions of the air-lift slurry bubble column with external looping as the adsorbing system, we studied, both theoretically and experimentally, the degree of circulation and the homogenization for the adsorbent slurry and compared with that of internal looping.

EXPERIMENTAL

The experiment was performed in the system of the air-lift bubble column. The size of the main column was 10 cm I.D. and 160 cm height, and looping column was 8 cm I.D. and the same height. The circulation characteristics and the degree of mixing were estimated by electroresistivity tracing from the residence time distribution curves of tracer with impulse input. The local gas holdups were measured from the local axial pressure distributions and the overall gas holdups from the expanded bed height.

Table 1. Experimental conditions

Experimental variables	Range of variables
Superficial gas velocity (cm/s)	2-10
Activated carbon	
Mean diameter (μm)	95.0
True density (g/cm^3)	2.50
Apparent density (g/cm^3)	1.20
Concentration of slurry (wt%)	2-8

The adsorbent was the activated carbon powder with a mean particle diameter of 95 μm and concentration of 0-8 wt%. The experimental condition is depicted in Table 1. The conductivity value of the circulating slurry phase was A/D converted and then stored in personal computer. The residence time distribution curves of tracer detected as the concentration of tracer by the electroresistivity probe were stored in the same way.

The mixing time was measured as the elapsed time from the startpoint to the point of 95% homogenization in the tracer concentration. And the circulation time was measured as the elapsed time between the peaks in the curves of residence time distribution.

RESULTS AND DISCUSSION

The air-lift slurry bubble column has many advantages as gas-liquid contactor and mixer in which fluidized particles are easily breakable and high efficiency of mixing is indispensable [Ochoa, 1997]. In this study, the air-lift slurry bubble column is used as a batchwise homogenizer where activated carbon powder is fluidized in the liquid medium with the gas input. The slurry flows are stably circulated in the system with vigorous contact of liquid-solid phase.

1. Circulation of Activated Carbon Slurry

The air-lift system has several advantages such as stable

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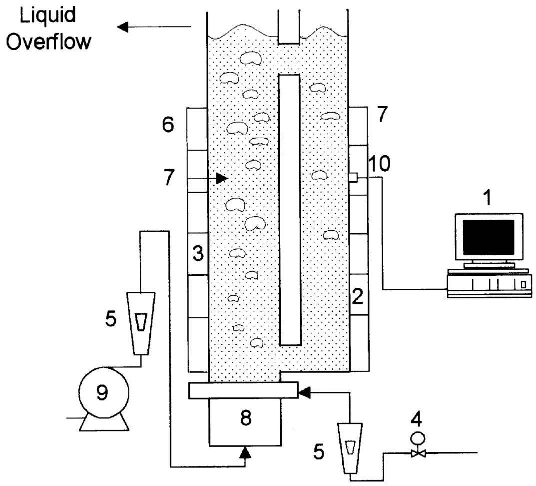

Fig. 1. Schematic diagram of experimental apparatus.

1. PC with A/D conversion	6. Thermocouples
2. Loop column	7. Tracer injector
3. Pressure taps	8. Distributor
4. Valves	9. Liquid pump
5. Flowmeter	10. Tracer detector

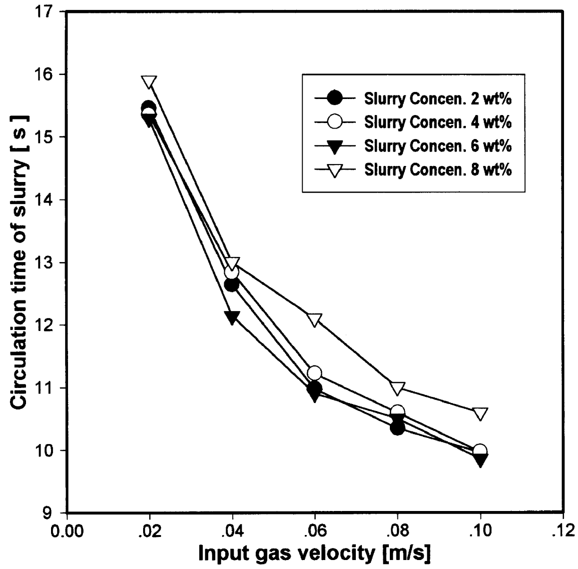

Fig. 2. Effect of input gas velocity on circulation time of slurry with concentration of activated carbon as parameter.

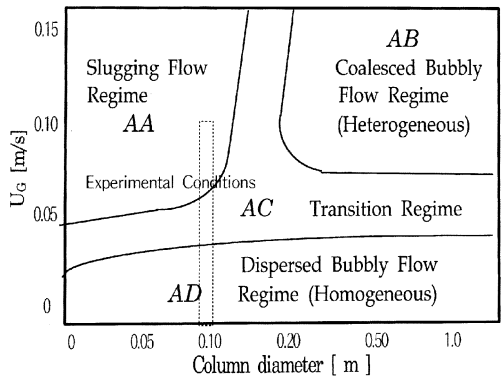

Fig. 3. Flow regime chart based on input gas velocity and column diameter with experimental conditions.

fluid motion due to separation of upward and downward flows, and high efficiency of suspending particles due to fast fluid flow. Slurry fluidization with looping can be described by the following equation:

$$C_r=\sum_{n=0}^{\infty}\left(\frac{Pe}{4\pi\theta}\right)^{1/2}\exp\left[-\frac{(X+n-\theta)^2}{4\theta}Pe\right] \tag{1}$$

where, $Pe=U_{SL}\,L_c/D_L$, $C_r=C/C_\infty$, $\theta=t/t_c$.

This equation contains much information about hydrodynamic characteristics such as the rate of circulation, degree of mixing and dispersion in a slurry. The circulation time of the activated carbon slurry decreased with the increase of gas velocity, but it increased with the increase of the concentration of slurry as shown in Fig. 2, and could be explained by the macroscopic energy balance equation, $C_1U_{SL}^2-C_2U_{SL}^{7/4}-C_3=0$ [Park, 1996]. But, in case of 4-8 cm/s gas velocity, the rate of circulation was enhanced due to the promoted fluidization of slurry with coalescing of bubbles having 4-6 wt% concentration of slurry as shown in Fig. 2. These tendencies were similar to the system with internal looping [Park, 1998], but the rate of circulation was more enhanced in the external looping system than internal one because of less friction loss in the flow. Therefore, the coalescence of bubbles is favorable in terms of the homogenizer or mixer because mixing effect is promoted by increased rising velocity of coalescing bubbles.

In view of the flow regime, our gas velocities are classified as the region illustrated by the dotted lines in the Fig. 3 which is proposed by Barnea [Fan, 1985]. This chart is the guideline for the state of the hydrodynamics in an air-lift slurry bubble column. As shown in the figure, the flow regime of this experiment is bounded in AA, AC and AD (dispersed bubbly, transition and slug flow). This flow regime chart is a function of length parameter, that is, column diameter and input gas velocity.

In the adsorption process, there are many factors affecting the rate of adsorption such as the concentration and dispersion degree of adsorbate, viscosity and surface tension of liquid and mixing rate of liquid. The mixing rate has a close relationship with rate of adsorption [Noll, 1992]. The flow regime formed by gas in slurry flow suggests much information for the circulation rate of a slurry, and is directly related to the rate of mixing because the flow regime is formed by the degree of bubble coalescence which determines the state of slurry circulation and mixing. Circulation time has a intimate relation with the concentration of activated carbon slurry which has a strong influence on the bubble coalescence affecting hydrodynamics of a contacting adsorber.

2. Characteristics of Homogenization with Transition of Flow Regime

Fig. 4 shows the change of mixing time of activated carbon slurry with respect to the input gas velocity at the concentration of activated carbon. Mixing rate is dependent on the dynamics of bubbles, gas holdups and the rate of slurry circulation. The degree of homogenization, Γ, which was defined as $(C-C_\infty)/C_\infty$, was used to calculate the time of mixing, where C and C_∞ means the tracer concentration at an arbitrary time and one at

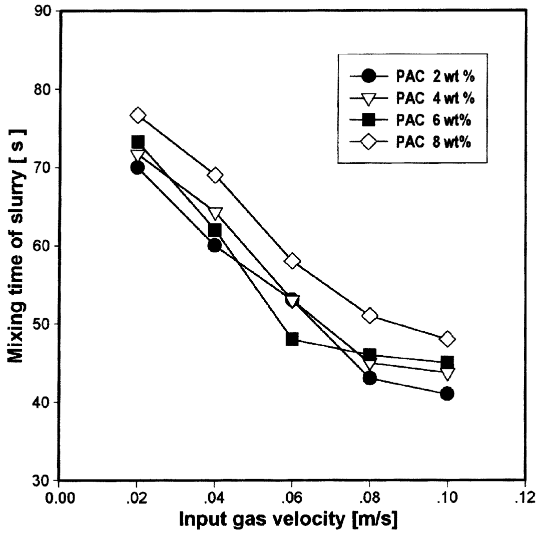

Fig. 4. Effect of input gas velocity on mixing time of slurry with concentration of activated carbon as parameter.

homogenized condition.

As shown in the figure, the mixing time is decreased exponentially with the increase of gas velocity and has similar tendency for the various concentrations of activated carbon slurry. The homogenization of slurry is directly related with the circulation of slurry, and the main driving force for circulation is the difference of gas holdups in activated carbon slurry between the riser and downcomer section of the system. The total gas holdups related with flow regimes [Ohkawa, 1997] were estimated from the height of bed expansion, and decreased with increasing slurry concentration. These phenomena are due to the non-uniform axial distribution of activated carbon slurry. As the gas velocity increased further, this phenomenon disappeared. Drift flux of gas relative to slurry, V_{GSL}, was used for the determination of flow condition and calculated by the following equation [Fan, 1989];

$$V_{GSL}=[(1-\varepsilon_G)/\varepsilon_{SL}](U_G\varepsilon_{SL}-U_{SL}\varepsilon_G) \quad (2)$$

where U_G, U_{SL} represent input velocity of gas and slurry, respectively, and ε_G, ε_{SL} represent holdup of gas and slurry, respectively. In this study, the flow regime was dispersed bubbly flow in low concentration of activated carbon slurry. But transition of flow regime to transition and slugging flow occurred with the increase of slurry concentration. This phenomenon can be explained by the coalescence of bubbles having an increase of slurry concentration, which results in an increase of the rising velocity of bubbles. Therefore, the increase of slurry concentration causes the transition of flow regime from bubbly and transition to slug flow, and these transition phenomena are desirable in view of an adsorbing contactor; but as activated carbon loading was increased to 8 wt%, the rate of circulation decreased as the result of overloading activated carbons. At a gas velocity of 6 cm/s, mixing time of 4 wt% slurry is nearly the same as 6 wt%. This means the activated carbon loading of 6 wt% shows almost the same mixing effect as that of 4 wt% due to enhancement of mixing by the coalescence of bubbles.

Compared with the internal looping contactor, the coalescence of bubbles was hindered at the same experimental conditions in general, because the liquid circulation rate was higher in external looping. For this reason, the optimum condition was different between the two systems, and in terms of solid loadings, the external looping system was more adequate because a larger amount of activated carbon was fluidized.

3. Performance of Airlift Bubble Column as Contactor

The air-lift bubble column has advantages such as efficient mixing and the prevention of solid breakage in the adsorbing contactor compared to other equipment that it can be applied in the process where these characteristics are indispensable. Especially in the case of fragile and fine particles, this system may be the most appropriate mixing equipment [Park, 1995]. But, compared to mechanical agitation, systematic analysis is not relatively easy, since the dynamic behavior is stochastic. For this system to be used as an efficient adsorber, the hydrodynamic behavior must be analyzed to find the optimal operating condition for high performance of the equipment.

The rate of energy dissipation, as mentioned earlier, has much information for the analysis of gas-liquid-solid fluidization [Chen, 1997], especially for this case of an air-lift contactor in the characteristics of heat, mass transfer and hydrodynamics such as fluid mixing and dispersions [Park, 1996]. The rate of energy dissipation is the energy consumed by microscale eddies which are produced by macroscale eddies in liquid phase created by rising bubbles. From Kolmogoroff's isotropic turbulence theory, these microscale eddies play an important role in the transport mechanism of interfacial relations. The energy dissipation used for liquid phase mixing was calculated [Park, 1998], and had a tendency to increase with the enhancement of mixing rate. This is due to the intense mixing of slurry phase by vigorous bubble agitations. Fig. 5 shows the relation between mixing time of slurry and the concentration of activated carbon. The mixing time at 4-6 cm/s gas velocities was decreased with the concentration of activated carbon slurry and had an optimal value at 6 wt% slurry concentration and 6 cm/s gas velocity.

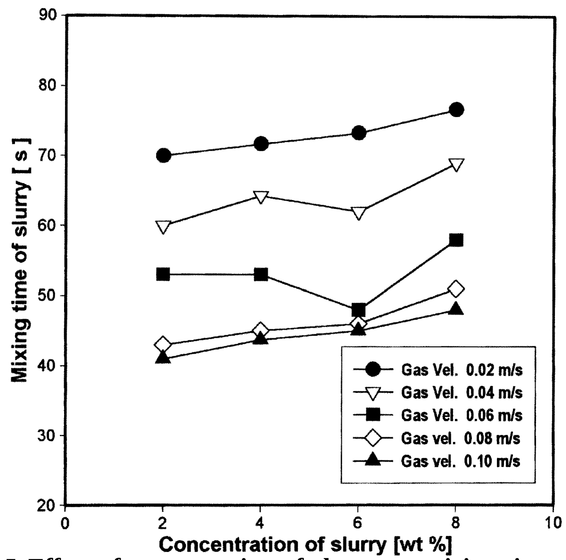

Fig. 5. Effect of concentration of slurry on mixing time with input gas velocity as parameter.

This is mainly because the enhanced liquid turbulence caused by bubble coalescence is high in that condition and the tendency is similar to the time of circulation as described above.

Compared to an internal looping system, the optimal condition was shifted from the activated carbon slurry concentration of 4 wt% and the input gas velocity of 4 cm/s to 6 wt% and 6 cm/s, respectively.

And, from the viewpoint of energy dissipation, external looping has a higher rate of energy dissipation than an internal looping system because of the friction factor for the direction of slurry flow and the difference of gas holdups. The mixing time of activated carbon slurry, t_m, can be expressed as follows:

$$t_m = k_1 t_c^2 U_{SL}^2 D_T^{-4/3} V_D^{-0.33} \quad (3)$$

where t_c, U_{SL}, V_D and D_T represent circulation time and averaged velocity of slurry, energy dissipation and column diameter, respectively. From the numerical fitting of this experiment, the empirical constant, k_1, was 2.52 and the regression coefficient was 0.95 with standard deviation of 0.03.

CONCLUSIONS

The hydrodynamic characteristics of an air-lift activated carbon slurry column having external looping were studied to find the optimal conditions of the system. The optimum activated carbon loading with gas inputs was both experimentally and theoretically obtained. The highest mixing rate was obtained in input gas velocities of 6 cm/s and in activated carbon concentration of 6 wt%. This is higher than the results obtained from internal looping. This phenomenon can be explained by the change of flow regime resulting from the coalescence of bubbles having an increase of activated carbon concentration.

NOMENCLATURE

C : concentration of tracer [kg/mol]
C_r : normalized concentration of tracer [-]
C_∞ : homogenized concentration of tracer [kg/mol]
D_L : mass diffusion coefficient [m^2/s]
D_T : length parameter [m]
k_1 : empirical constants
L_c : circulation length of fluid path [m]
n : number of fluid circulation [-]
Pe : Peclet number [-]
t_c, t_m : time of circulation and of mixing [s]
U_G : input gas velocity [m/s]
U_L : input liquid velocity [m/s]
U_{SL} : superficial slurry velocity [m/s]
V_D : energy dissipation rate by microeddies [m^2/s^3]
V_{GL} : drift flux of gas relative to liquid
X_C : normalized location of tracer input [-]

Greek Letters

θ : normalized time of elapse [s]
Γ : degree of homogenization [-]
ε_G : holdup of gas [-]
ε_{SL} : holdup of slurry [-]

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