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The Heat Transfer Characteristics in Air-Lift Contactor with Activated Carbon for the Separation of Air Pollutants

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Abstract−Correlation analysis of heat transfer and hydrodynamic characteristics of an air-lift activated carbon slurry contactor with bubble agitation, which is applied to the separation of air pollutant, wastewater treatment, and biological processes, was investigated in order to find the operating conditions of the separation process with thermal control for the purpose of efficient air pollutant scrubbing. Heat transfer was characterized with the internal heating of fluidizing slurry of powdered activated carbons and analyzed with the hydrodynamic characteristics, which were analyzed with the residence time distribution of the system. All experiments were conducted with the conditions of varying concentration of adsorbents and gas inputs in the air-lift bubble column with external looping as a batchwise contactor. From the studies, the best operating condition of the air-lift bubble column for the adsorbing equipment could be suggested.

Key words: Bubble Agitation, Heat Transfer, Fluidizing Slurry

INTRODUCTION

Slurry agitation by bubbles has overwhelming advantages compared to the mechanical mixing system in the field of environmental process which needs fluidization of particles for rapid transport of heat and mass with momenta. In particular, this method has high ability of treating fragile particles due to the fluidization of slurry flow with buffering action of liquid medium.

Adsorption by activated carbon has been widely used in the fields of odor removal, recovery of VOC's, and biological wastewater treatment [Wang, 1994]. In this case, active contact between adsorbents and adsorbate and thermal control are prerequisite conditions for high efficiency of gas-liquid-solid adsorption processes [Moon, 1986; Yun, 1997; Lee, 1997]. Therefore, the air-lift slurry bubble column can be applied very adequately for the simultaneous separation of pollutants with gas absorption and liquid adsorption by powdered activated carbons. But, there is little systematic study for the thermal control used for an adsorber in reactor design. In this study, heat transfer characteristics of activated carbon slurry with bubble agitation were investigated to make the contactor an efficient adsorbing system; simultaneously, the degree of activated carbon slurry circulation with the heat transfer was investigated.

EXPERIMENTAL

The experiment was conducted as a process of heat transfer studies with simultaneous hydrodynamic research in the air-lift activated carbon contactor. The size of main column is 15 cm I.D, 160 cm high and a downcomer tube is 10 cm I.D., same height with external looping of fluid. The circulation characteristics and the degree of mixing were estimated from the residence time distribution curves of a tracer with impulse input, and the local gas holdups were measured from the axial pressure distributions and the overall gas holdup by measuring the change of bed height. The adsorbent was powdered activated carbon with mean particle size of 75 micron less than that applied in the previous study [Park, 1998]. Heat transfer study was conducted with the measurement of heat transfer coefficient from the immersion heater-to-slurry experiment. The detailed condition of this study is depicted in Table 1 and the schematic diagram of experimental apparatus in Fig. 1. The temperature value of the circulating slurry phase was A/D converted and then stored in a personal computer, and the residence time distribution curves of tracer were detected as conductivity values by the electroresistivity probe and converted to the concentration of the tracer and stored in the same way.

Heat transfer coefficient was calculated from the following equation suggested by Newton's law of cooling.

$$h=Q/(\Delta T\cdot A) \qquad (1)$$

Table 1. Experimental ranges for tested condition

Experimental variables	Range of variables
Input gas velocity (cm/s)	2-10
Activated carbon	
Mean diameter (μm)	75.0
True density (g/cm^3)	2.50
Apparent density (g/cm^3)	1.20
Temperature (°C)	15-30
Concentration of slurry (wt%)	0-8

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‡This paper is dedicated to Professor Dong Sup Doh on the occasion of his retirement from Korea University.

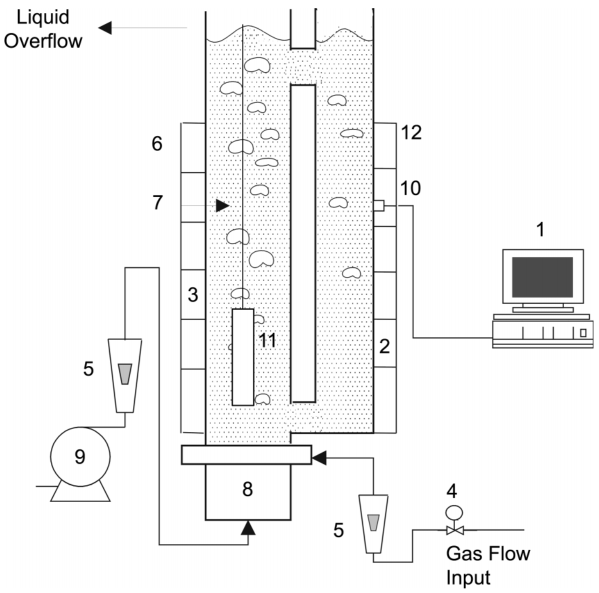

Fig. 1. Schematic diagram of experimental apparatus.

1. PC system	7. Tracer injector
2. Downcomer	8. Gas distributor
3. Riser	9. Liquid pump
4. Needle valve	10. Tracer detector
5. Flow meter	11. Immersion heater
6. Pressure taps	12. Thermocouples

where ΔT is the difference of temperature between the surface of heater and fluidizing adsorbents and A is the surface of heater. Q is the heat quantity supplied to the fluidizing system per unit time which was estimated by the Eq. (2).

$$Q=m_{SL}C_{PSL}(T_{SLf}-T_{SLi}) \quad (2)$$

where m_{SL}, C_{PSL} are the mass of slurry and specific heat of slurry, and T_{SLf} and T_{SLi} are final and initial temperature of slurry, respectively.

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

An adsorbing contactor is commonly classified as fixed bed, pulsed bed, moving bed, and fluidized bed equipment. Air-lift contactor is in the form of a fluidized bed and has so many advantages that it is frequently applied in the separation technology where treated particles are small and breakable and gas phase is soluble with high efficiency of mixing indispensable. In our study, an Air-lift slurry system is used as a batchwise scrubber where activated carbon particles are mobilized in the liquid medium with the gas energy. In this case information for slurry flows such as hydrodynamics, heat and mass transfer is indispensable because it suggests many design parameters concerning an efficient contacting separator [Fan, 1989].

1. Heat Transfer

In view of flow regime, our gas velocities are classified as the homogeneous bubbly flow and transition range in terms of flow regime [Fan, 1989]. Fig. 2 shows the heat transfer of activated carbon slurry vs. the input gas velocity with the concentration of powdered activated carbon as parameters. Heat transfer rate in the multiphase contactor is chiefly dependent on the dynamics of bubbles, gas holdups and the rate of slurry mixing and circulation due to fluidization.

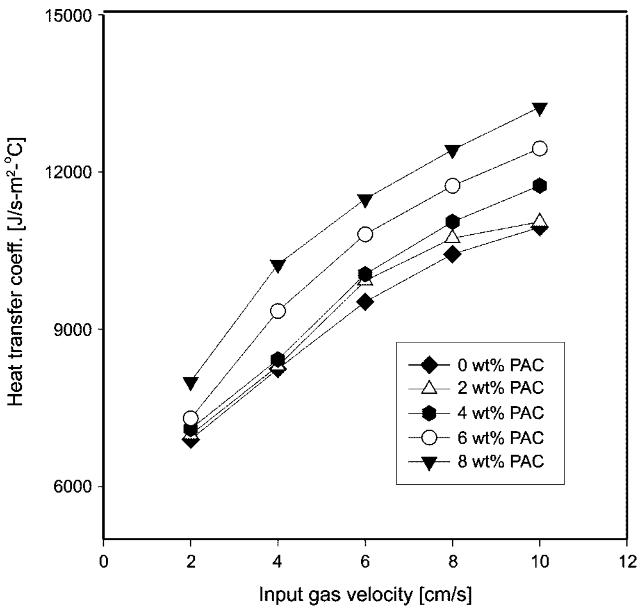

Fig. 2. Tendency of heat transfer coefficient vs. input gas velocity with the concentration of PAC slurry.

As shown in the figure, the heat transfer coefficient increases with the rise of gas velocity and has similar tendency for the increase of activated carbon slurry concentration. This phenomenon is explained as the main driving force for the heat transfer coefficient is the degree of slurry agitation, which is related with volume fraction of gas phase between the riser and downcomer section of slurry. Therefore, heat transfer in the activated carbon slurry is mainly influenced by the factor of bubble coalescence.

This tendency is similar to the mixing time for the same reason, that is, due to the enhanced liquid turbulence caused by coalescence of bubbles. This phenomenon can be explained as the shift of flow regime due to activated carbon slurry causing an enhancement of heat transfer, and consequently causing the increased circulation rate of activated carbon; this is agrees with the tendency of energy dissipation which can be expressed in Eq. (3) [Park, 1998].

$$h=k(\rho_{SL}C_{pSL}K_{SL}V_D^{1/2}\gamma_{SL}^{-1/2})^{1/2} \quad (3)$$

where ρ_{SL}, C_{pSL}, K_{SL} are density, specific heat and thermal conductivity of adsorbent slurry and γ_{SL} is kinematic viscosity, V_D is the rate of energy dissipation which was estimated in our previous study [Park, 1998]. Heat transfer coefficient increased as the gas velocity increased further to reach transition, but the rate of increase was diminished gradually for the range of powdered activated carbon concentration, as can be seen in Fig. 2. From the correlation of experimental data, it could be obtained that empirical constant k was 0.0125 with regression coefficient of 0.95 within the experimental range.

2. Hydrodynamics

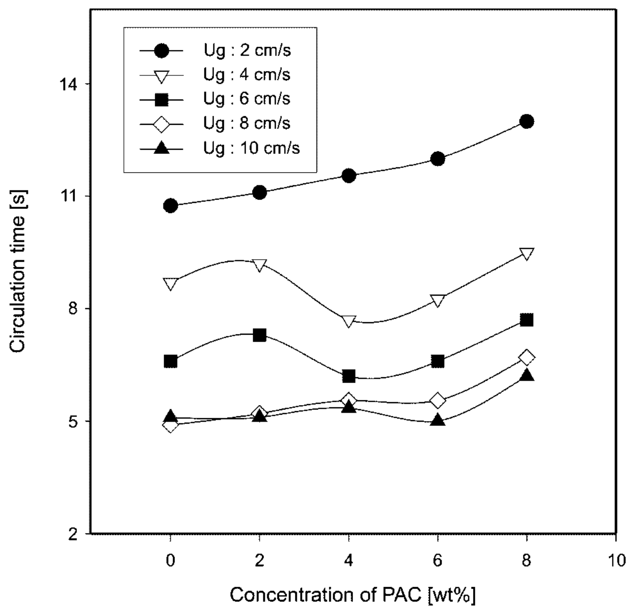

Fig. 3. Tendency of circulation time vs. concentration of PAC slurry with input gas velocity.

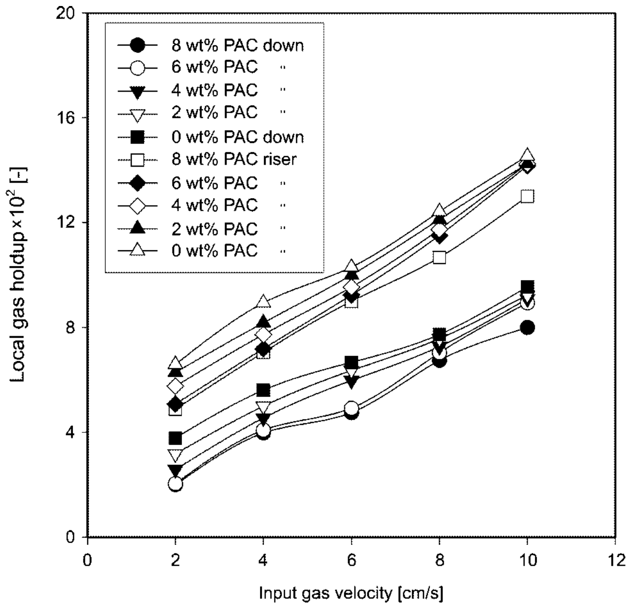

Fig. 4. Tendency of local gas holdup vs. input gas velocity with concentration of PAC slurry.

The motion of activated carbon slurry with bubble agitation is chaotic and cannot be easily analyzed exactly. Therefore, a population balance model can be adopted such as residence time distribution, and can be described by the following equation:

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

where $Pe=U_{SL}L_c/D_L$, $C_r=C/C_\infty$, $\theta=t/t_c$ and X, n, θ mean normalized location of tracer input, number of fluid circulation and normalized time of elapse, respectively.

In this study the main theme is the characteristic of heat transfer in the slurry contactor; therefore the above Eq. (1) suggests a great deal of information relating to heat transfer such as the rate of circulation and degree of mixing. The circulation rate of activated carbon slurry had a strong relationship with the heat transfer coefficient. Fig. 3 explains the tendency of circulation time with the concentration of PAC in the varied range of input gas velocity.

The circulation time showed a similar tendency in 2 wt% of PAC concentration compared to solid free values, but as the PAC concentration increased further, the circulation time decreased to minimal values in 4 wt% of PAC concentration and then increased gradually. And these tendencies are closely related to the change of bubble behavior due to the physical properties of activated carbon slurry. Bubbles are coalesced in the presence of fine particles, and this phenomenon causes momentum change of slurry; these phenomena appeared in the range of 4-6 cm/s with the circulation of PAC slurry. Therefore, adsorbent mixing and heat transfer may be efficient in this experimental range.

Heat transfer characteristics of activated carbon slurry enhanced due to the promoted fluidization of slurry with the bubble coalescence as the concentration of slurry increased. Therefore, the coalescence of bubbles is favored in terms of heat transfer controls in the gas-liquid contacting adsorber. But in view of gas scrubbing, bubble coalescence is not desirable as the interfacial area needed for mass transfer becomes smaller.

Fig. 4 explains that the local gas holdups in the riser column and downcomer column are diminished as the concentration of PAC increases, which explains the coalescence of bubbles and overall tendencies of holdups are similar to those with the slurry of glass beads [Park, 1995].

3. Correlation of Hydrodynamics and Heat Transfer

The heat transfer in air-lift slurry is mainly dependent on the mobility of slurry and bubble characteristics. The main factors related are the bubble coalescence and rising velocity, and these are determined by slurry properties such as viscosity, heat capacity, thermal

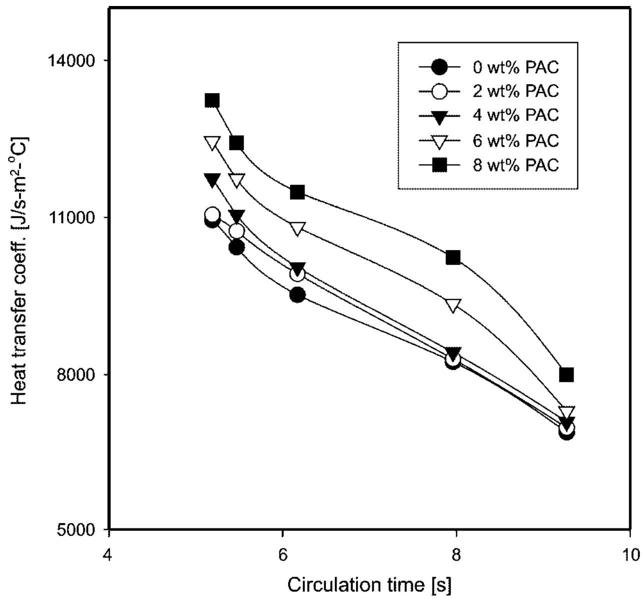

Fig. 5. Tendency of heat transfer coefficient vs. circulation time of PAC with concentration of slurry.

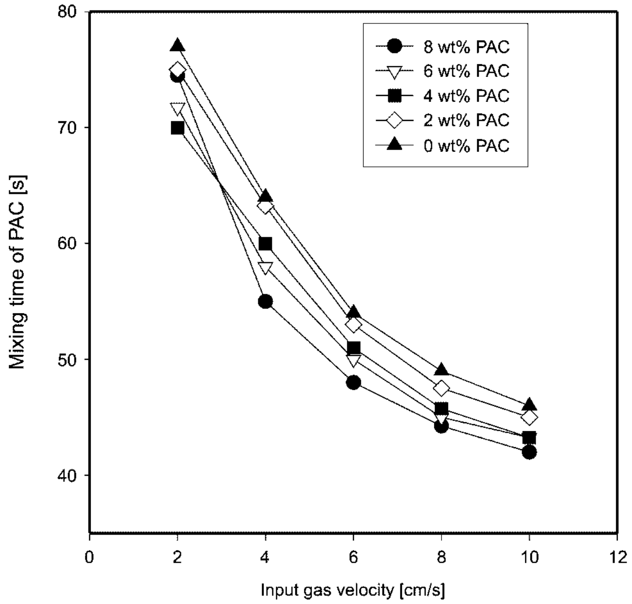

Fig. 6. Tendency of mixing time vs. input gas velocity with concentration of PAC slurry.

conductivity, density, and energy dissipation rate as explained in the above section.

Fig. 5 is the relation of the heat transfer coefficient with the circulation time of powdered activated carbon slurry in various concentrations of slurry. As given in the figure, the heat transfer coefficient is decreased abruptly in bubbly flow and rate of decrease diminishes as the circulation time increases, and then goes down in the form of exponential decay. It can be seen clearly that the heat transfer coefficient is strongly dependent on the powdered activated carbon slurry circulation with bubble mixing.

With the vigorous agitation of slurry flow in bubble agitated contactor the designed temperature uniformity can be processed by limiting the rate of heat transfer or reducing the heat transfer surface area, but the efficiency can be changed with the change of fluidizing medium properties.

The efficiency of adsorption primarily depends on concentration, viscosity of solution, and the extent of agitation [McKay, 1996]. And the most important parameter is the extent of mixing or homogenization in the contactor. Fig. 6 explains the tendency of mixing phenomena with input gas velocity varying the concentration of adsorbent slurry.

The increase of bubble coalescence induces the increase of energy dissipation rate [Park, 1998] which is related with the rate of heat and mass transport. The change of energy dissipation is caused by the intense mixing of liquid phase by vigorous bubble agitation. In conjunction with isotropic turbulence fluid microeddies, which are related to energy dissipation, particles contribute to heat transfer [Fan, 1989]. Air pollutants can be scrubbed by liquid and then adsorbed by activated carbons for separation which are main advantages compared to other processes for separation. In this case the amount of activated carbons and contact time are main operating factors for effective adsorption processes.

The design of industrial adsorbers needs a great amount of information, and the most important parameters are thermal control and the degree of mixing from the residence time intimately related to the size and the geometry of equipment. From the viewpoint of air pollutant separation process, the bubble coalescence hinders the interfacial mass transfer but enhances the turbulent mixing of the phases. Therefore, the optimal loadings of adsorbents should be decided from the comparison of two opposing conditions.

CONCLUSIONS

The adsorptive separation process by air-lift slurry agitation is the typical application in the field of multiphase contactors, and this process requires knowledge of hydrodynamic and thermal behavior of three phase slurry to make the separation as highly efficient as possible. Therefore, the heat transfer with hydrodynamics for activated carbon loadings with gas inputs was studied. From this experiment, heat transfer could be enhanced with the loading of activated carbons in the given range of gas velocity, and it could be found that the circulation and mixing was enhanced with that condition. Especially in case of simultaneous gas absorption and liquid separation needed, this system might be the most appropriate equipment. Optimal loadings of activated carbon for simultaneous gas absorption and separation of air pollutants would be continued. And the transport phenomenological study of this system would be done for application in industrial fields.

NOMENCLATURE

A	: surface area of heater [cm^2]
C	: concentration of tracer [g/mol]
C_p	: specific heat [cal/g·°C]
C_r	: normalized concentration of tracer [-]
C_∞	: homogenized concentration of tracer [g/mol]
D_L	: mass diffusion coefficient [cm^2/s]
h	: heat transfer coefficient [J/m^2-°C-s]
k	: empirical constants
K	: thermal conductivity [cal/°C-s-g]
L_c	: circulation length of fluid path [cm]
m_{SL}	: mass of slurry [g]
n	: number of fluid circulation [-]
Nu	: Nusselt number [-]
Pr	: Prandtl number [-]
Q	: heat quantity supplied to fluidizing system [J/s]
Re	: Reynolds number [-]
T	: temperature [°C]
t_c, t_m	: time of circulation and of mixing [s]
V_D	: rate of energy dissipation [cm^2/s^3]
X	: normalized location of tracer input [-]

Greek Letters

θ	: normalized time of elapse [s]
γ	: kinematic viscosity [cm^2/s]
ρ	: density [g/cm^3]

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