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Residence time distribution and dispersion of gas phase in a wet gas scrubbing system

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Abstract−Residence time distribution (RTD) of exhaust gas in a wet scrubbing system was investigated for application to the removal of SO_x, NO_x or dust included in exhaust gas. The mixing of gas phase in the wet scrubbing system was also examined by considering the axial dispersion coefficient of gas phase. Effects of gas amount (velocity), liquid amount (velocity) and solid floating materials on the residence time distribution (RTD) and axial dispersion coefficient of exhaust gas were discussed. The addition of solid floating materials could change the RTD and thus dispersion of exhaust gas in the scrubbing system. The mean residence time and axial dispersion coefficient of exhaust gas were well correlated in terms of operating variables.

Key words: Gas RTD, Wet Scrubbing System, Gas Dispersion Coefficient, Floating Materials

INTRODUCTION

A wet scrubbing system, which can be applicable to the removal of SO_x, NO_x or dust included in the exhaust gas, involves gas-liquid countercurrent flow. In this countercurrent flow system, the addition of floating solid particles can increase the contacting efficiency between the gas and the liquid phases effectively. Since the liquid flows easily downward from the top of the system, the solid particles with a lower density would be more convenient to be floated in the continuous flow of liquid phase [1-3].

To understand the phenomena of dispersed gas phase flow in this wet scrubbing system, the estimation for the extent of longitudinal dispersion of gas, as well as hydrodynamic characteristics are essential. Thus, several studies have been done to account for the dispersion characteristics of dispersed gas phase by means of residence time distribution (RTD) [4,5].

To estimate the gas dispersion in the flow system, bimodal axial dispersion and two-bubble-class models for the churn turbulent flow regime were proposed [6,7]. These models assume a unique average velocity and a unique dispersion coefficient of each bubble group. A fully developed convective model based on the kinetic theory was developed, which was used for the determination of an absolute bubble velocity distribution [8]. However, little attention has been focused on the residence time distribution and dispersion of gas phase in the gas-liquid countercurrent flow scrubbing system.

In the present study, the dispersion of gas phase in a wet gas scrubbing system is examined by considering the residence time distribution. Effects of gas and liquid amounts (velocities) and solid floating materials on the residence time distribution (RTD) and axial dispersion coefficient of gas phase are discussed. The mean residence time and axial dispersion coefficient of exhaust gas have been correlated in terms of operating variables.

EXPERIMENTAL

Experiments were carried out in a wet scrubbing system which was made of an acrylic column (0.152 m in diameter and 2.5 m in height), as shown in Fig. 1. The liquid distributor was situated between the main column section and a stainless-steel box, from which the liquid phase was withdrawn downward. At the bottom, the gas

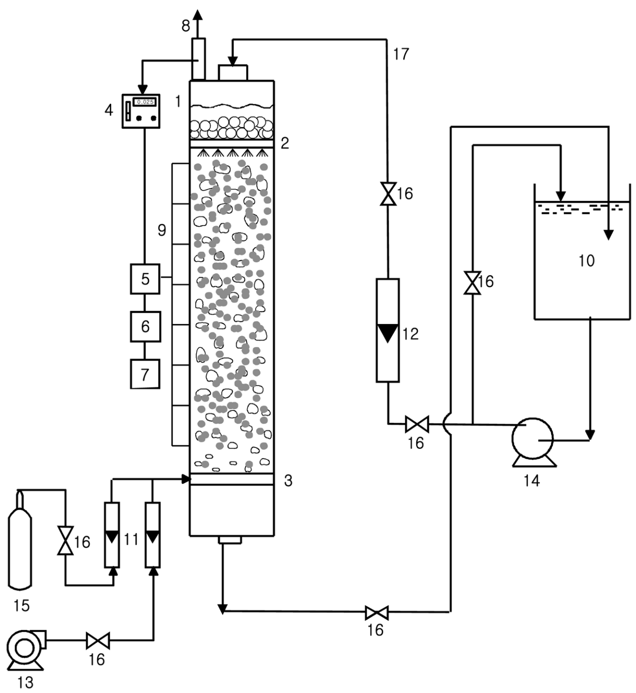

Fig. 1. Schematic diagram of experimental apparatus.

1. Liquid calming section
2. Liquid distributor
3. Gas distributor
4. CO analyzer
5. Amplifier
6. Data acquisition system
7. Personal computer
8. Gas vent line
9. Pressure taps
10. Liquid reservoir
11. Gas flowmeter
12. Liquid flowmeter
13. Air compressor
14. Pump
15. CO gas bomb
16. Control valve

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was fed to the column through four evenly spaced 6.35 mm distributor pipes which contained 28 holes of 1 mm in diameter. The flow rates of gas and liquid phases were measured by flow meters and regulated by means of globe valves on the feed and bypass lines. Pressure taps for measuring the dynamic pressures by pressure sensors were mounted flush with the wall of the column at 0.1 m or 0.2 m above the gas distributor. Compressed filtered air was used as the gas phase and water as the liquid phase. Either polyethylene (PE) or polypropylene (PP) beads, with a density of 966.6 or 877.3 kg/m^3, respectively, were used as the solid floating materials. The diameter of floating particles was 4.0 mm. The compressed CO gas was used as a tracer to measure the residence time distribution of gas phase in the system. The CO gas was fed into the line of gas input as a delta function, forming a plane source at the gas distributor. The CO gas was detected continuously in the gas vent line at the top of the column, by means of CO analyzer (GreenLine 6000, EUROTRON).

DETERMINATION OF RTD AND DISPERSION COEFFICIENT

The longitudinal dispersion model is the simplest mathematical description of a flow system in which both convection and diffusion are important. From the analogy between Fick's law for molecular diffusion and the dispersion process, Eq. (1) can be written for the dispersion phenomenon with the following basic assumptions:

(1) The gas velocity distribution is uniform throughout the cross-sectional area; (2) bulk flow exists only in the axial direction; (3) gas-phase dispersion exists in axial direction only and the axial dispersion coefficient is independent of spatial co-ordinates; and (4) axis-symmetric tracer concentration distribution exists. The first assumption could be reasonable in this system, since the rising bubbles, which can generate the radial velocity profile of gas phase, could be broken down by means of floating materials.

$$\frac{\partial C}{\partial t} = D_z \frac{\partial^2 C}{\partial Z^2} - \frac{U_G \partial C}{\varepsilon_G \partial Z} \tag{1}$$

Where the parameter D_z is the axial dispersion coefficient of gas phase, uniquely characterizing the degree of mixing during the flow. The analytical solution of Eq. (1) for the normalized response curves can be written as Eq. (2) [9];

$$C_\theta = \frac{1}{2\sqrt{\pi\theta/Pe}} \exp\left[-\frac{(1-\theta)^2 Pe}{4\theta}\right] \tag{2}$$

where $1/Pe=(\varepsilon_G D_z/U_G L)$, $C_\theta=C/C_0$ and $\theta=t/t_m$, respectively, and C is the tracer concentration of collected sample at time t and C_0 is the input tracer concentration. The distance (L) between the points of tracer injection and the measuring plane has been considered as positive in the direction of flow. A method of moments has been used to estimate the axial dispersion number (1/Pe) by the following equation by taking of average of four repeated experiments [1].

$$\sigma_\theta^2 = \frac{\sigma^2}{t_m^2} = \frac{2}{Pe} + \frac{8}{Pe} \tag{3}$$

Here t_m and σ were calculated, respectively, as:

$$t_m = \frac{\sum t_i C(t_i)\Delta t_i}{\sum C(t_i)\Delta t_i} \tag{4}$$

$$\sigma^2 = \frac{\sum (t_i - t_m)^2 C(t_i)\Delta t_i}{\sum C(t_i)\Delta t_i} \tag{5}$$

RESULTS AND DISCUSSION

Effects of gas and liquid velocities (superficial velocity) on the gas holdup in the scrubbing system can be seen in Fig. 2. In this figure, the gas holdup increases with increasing gas or liquid velocity, but the effect of gas velocity is predominant. The increase of gas velocity results in the increase of input gas amount. The increase of liquid velocity can disturb the rising of dispersed gas phase. Thus, the value of gas holdup increases. Note that the addition of floating solid particles into the scrubbing system can lead to an increase in the gas holdup. This can be due to the hindrance effects of floating particles on the rising gas phase [4,10-13]. It is interesting to note that when the polyethylene particles (ρ=877.3 kg/m^3) were added in the scrubbing system, the gas holdup exhibited a lower value than that in the condition of no particles, at the relatively lower ranges of U_G (0.2-0.4 cm/s) and U_L (1.0-1.5 cm/s). These phenomena are

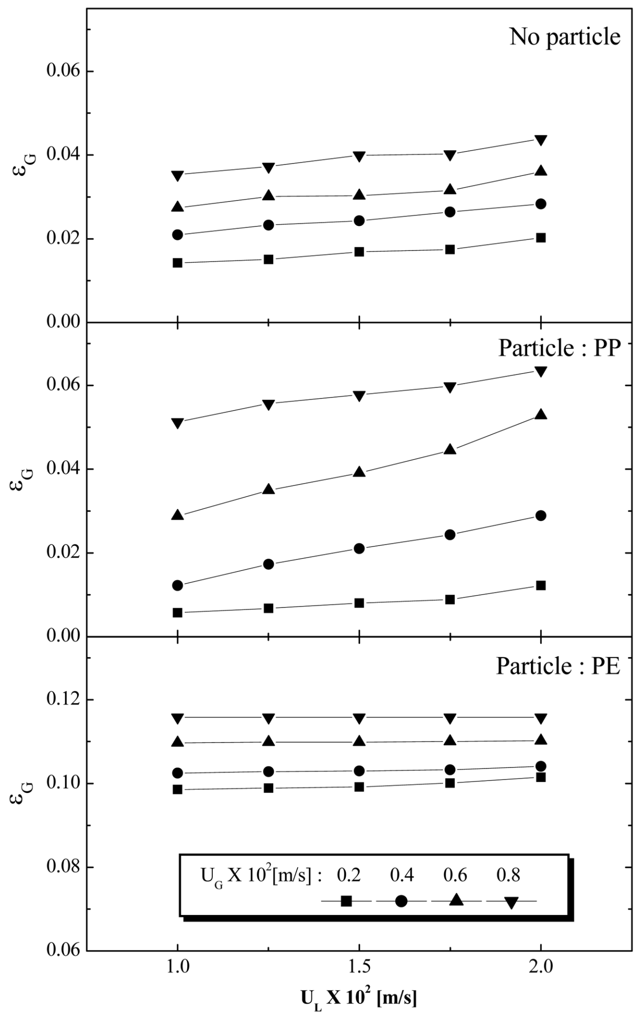

Fig. 2. Effects of gas and liquid velocities on the gas holdup in the wet scrubbing system.

similar to the bed contraction in the column where the gas and liquid flow cocurrently in the upwards direction [13-15]. However, these phenomena in the gas/liquid countercurrent flow system have not been reported elsewhere until now.

Typical residence time distribution (RTD) of tracer gas in the scrubbing system can be seen in Fig. 3. In this figure, the E-curve of distribution becomes broad but its mean value decreases with increasing gas velocity. It has been understood that the mean residence time of gas phase in the system decreases with increasing gas velocity. However, with increasing U_G, the amount of dispersed phase in the system increases, and thus, the residence time of dispersed gas phase

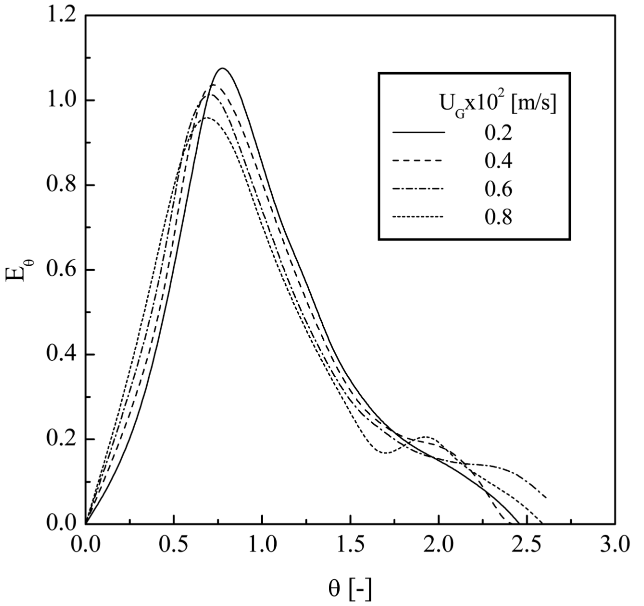

Fig. 3. Residence time distribution (RTD) of gas phase in the wet scrubbing system with variation of U_G (U_L=2.0 cm/s, particle: PP).

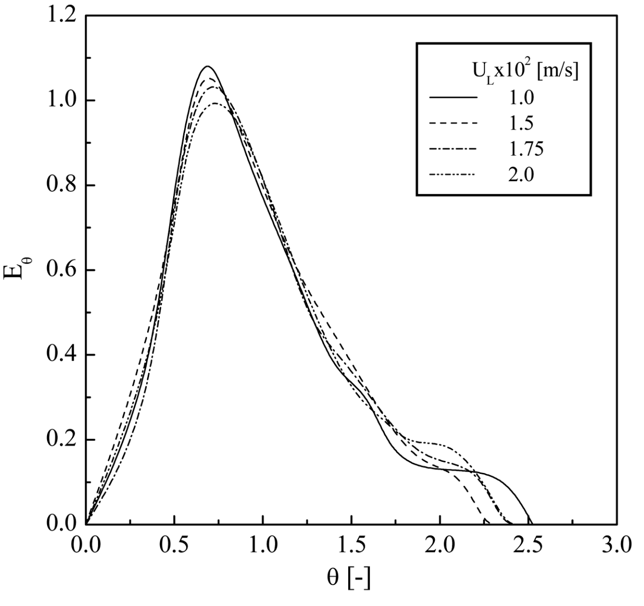

Fig. 4. Residence time distribution (RTD) of gas phase in the wet scrubbing system with variation of U_L (U_G=0.4 cm/s, particle: PP).

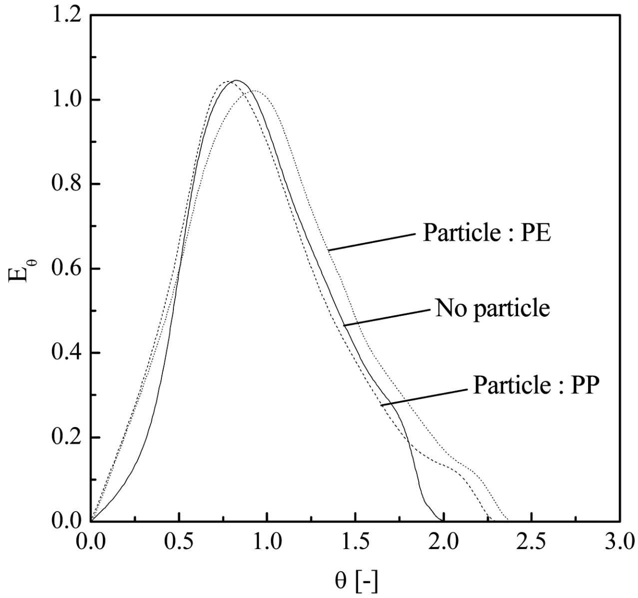

Fig. 5. Effects of floating solid materials on the residence time distribution (RTD) of gas phase in the wet scrubbing system (U_G=0.4 cm/s, U_L=1.5 cm/s).

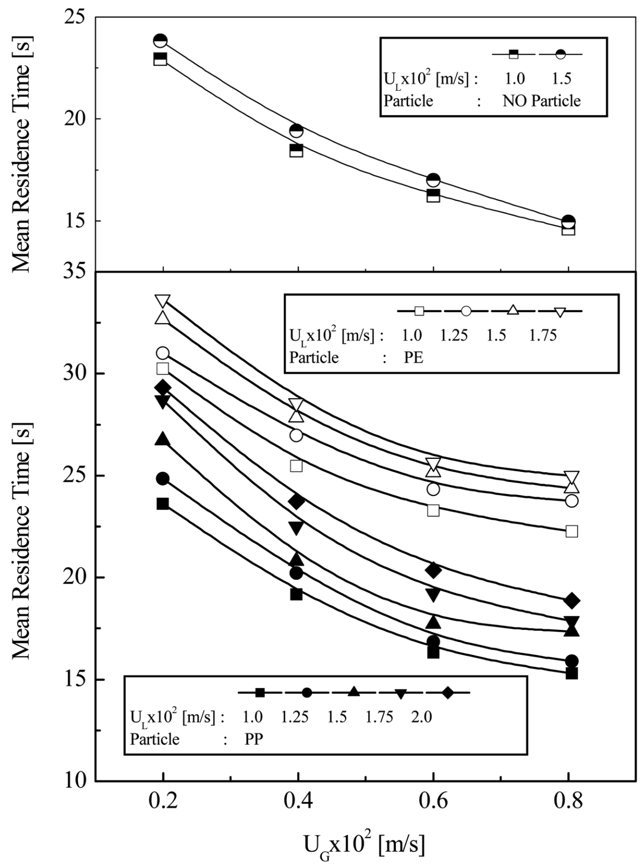

Fig. 6. Effects of U_G on the mean residence time of gas phase in the wet scrubbing system.

would be more scattered. Therefore, the RTD curve trends to be board with increasing U_G. From the data of these RTD curves, the values of t_m and D_z were determined. Effects of liquid velocity on the residence time distribution of gas phase can be seen in Fig. 4. In this figure, the curve becomes broad and its mean value increases with increasing U_L, as can be expected, since the holdup of gas phase increases with increasing U_L as mentioned earlier.

Effects of floating solid materials on the RTD of gas phase can be seen Fig. 5. In this figure, the addition of floating solid particles could lead to two kinds of shift of RTD curve of gas phase compared with that with no floating solid materials. In the case of the addition of polypropylene, the RTD curve shifted to the left-hand side; on the other hand, the injection of polyethylene particles let the RTD curve shift to the right-hand side.

The values of mean residence time of dispersed gas phase in the wet scrubbing system, which were determined from the RTD curves, are described in Fig. 6. The mean residence time of gas phase decreases with increasing gas velocity but increases with increasing U_L.

The values of axial dispersion coefficient of dispersed gas phase can be seen in Fig. 7, with the variations of operating variables. The axial dispersion coefficient of gas phase increases with increasing U_G but decreases with increasing U_L. The mean residence time and axial dispersion coefficient of gas phase in the scrubbing system have been well correlated in terms of operating variables as Eqs. (6) and (7), respectively. The correlation coefficient of the former is 0.97 and that of the latter is 0.96. The calculated value of D_z was well fitted to that of experimentally determined, as can be seen in Fig. 8.

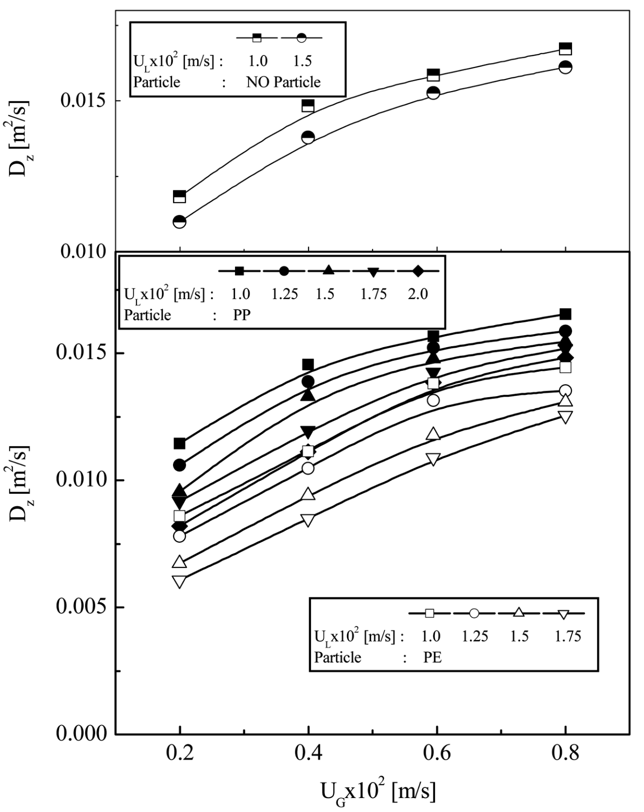

Fig. 7. Effects of U_G on the axial dispersion coefficient of gas phase in the wet scrubbing system.

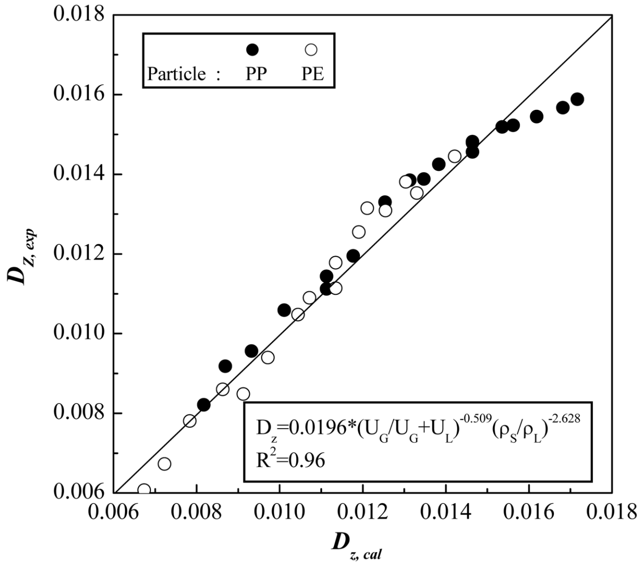

Fig. 8. Comparison of experimental and calculated values of axial dispersion coefficient in the wet scrubbing system.

$$t_m = 17.619\left(\frac{U_G}{U_G+U_L}\right)^{-0.363}\left(\frac{\rho_S}{\rho_L}\right)^{3.005} \tag{6}$$

$$D_z = 0.0196\left(\frac{U_G}{U_G+U_L}\right)^{-0.509}\left(\frac{\rho_S}{\rho_L}\right)^{-2.628} \tag{7}$$

The information on the mean residence time and axial dispersion coefficient of dispersed gas phase in the wet gas scrubbing system can be used to predict the scrubbing time, amount of liquid required and efficiency of gas scrubbing in the system.

CONCLUSION

1. The axial dispersion coefficient of the dispersed gas phase was successfully determined in a countercurrent wet scrubbing system by means of axial dispersion model from the data of RTD in the system.
2. The effects of the addition of floating solid materials on the RTD of gas phase were considerable; the addition of polyethylene particles could let the RTD curve shift to the left-hand side, but in case of polyethylene particles, the RTD curve shifted to the right-hand side in comparison with the RTD curve with no floating solid materials.
3. The mean residence time of gas phase decreased with increasing gas velocity but increased with increasing U_L. The axial dispersion coefficient of gas phase increased with increasing U_G but decreased with increasing U_L.
4. The mean residence time and axial dispersion coefficient of gas phase were well correlated in terms of operating variables as:

$$t_m = 17.619\left(\frac{U_G}{U_G+U_L}\right)^{-0.363}\left(\frac{\rho_S}{\rho_L}\right)^{3.005}$$

$$D_z = 0.0196\left(\frac{U_G}{U_G+U_L}\right)^{-0.509}\left(\frac{\rho_S}{\rho_L}\right)^{-2.628}$$

NOMENCLATURE

C : tracer concentration of collected sample at time t [kg/m^3]

C_0 : input tracer concentration [kg/m^3]
C_θ : normalized concentration [C/C_0]
D_{ax} : longitudinal dispersion coefficient [m^2/s]
Pe : Peclet number, dimensionless
RTD : residence time distribution
t : time [s]
t_m : mean residence time [s]
U_G : superficial gas velocity [m/s]
Z : axial length [m]

Greek Letters

ε_G : fractional gas hold-up, dimensionless
θ : dimensionless time (t/t_m), dimensionless
ρ_S : density of solid phase [kg/m^3]
ρ_L : density of liquid phase [kg/m^3]

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