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Particle Removal Efficiency of Gravitational Wet Scrubber Considering Diffusion, Interception, and Impaction

H. T. Kim,[1] C. H. Jung,[1] S. N. Oh,[2] and K. W. Lee[1,*]

[1]Department of Environmental Science and Engineering
Kwangju Institute of Science and Technology
Puk-Gu, Kwangju 500-712, South Korea
[2]Applied Meteorology Research Laboratory
Meteorological Research Institute/KMA
Dongjag-Gu, Seoul 156-720, South Korea

ABSTRACT

A method of predicting the particle removal efficiency of gravitational wet scrubbers and the particle size distribution properties, that considers diffusion, interception, and impaction, is presented to study the particle removal mechanisms of gravitational wet scrubbers. This method assumes a lognormal size distribution of aerosol particles as well as three additive collection efficiencies. Thus, the overall collection efficiency is described as the sum of all three. It is represented as a U-shaped curve with a minimum in the region of around 1.0 μm in particle diameter. This allows aerosols in the diffusion- and in the impaction-dominant regions to be removed at a higher rate compared with aerosol in the intermediate region. As aerosols pass through the gravitational wet scrubber, the geometric standard deviations of the size distribution of polydispersed aerosols decrease. The geometric mean diameter of aerosol in the diffusion-dominant region increases, whereas it decreases in the impaction-dominant region. The present study also shows that in optimum operation conditions such as low droplet falling velocity, small droplet size, and high liquid-to-gas flow ratio, the gravitational wet scrubber has sufficient ability to remove particles whose diameters are much smaller than 1.0 μm.

Key words: aerosol; diffusion; impaction; polydisperse; lognormal distribution

INTRODUCTION

Emission control equipment commonly used to remove particles includes wet scrubbers, electrostatic precipitators, cyclones, and fabric filters. The wet scrubber is an effective tool in removing particles as it brings particle-laden gas into contact with liquid droplets. The scrubbing mechanisms are represented by diffusion, interception, inertial impaction, and gravitational settling. Among these mechanisms, inertial impaction remains an important mechanism for capture of particles larger than 5.0 μm, while diffusion is essential for capture of smaller

*Corresponding author: Department of Environmental Science and Engineering, Kwangju Institute of Science and Technology, 1 Oryong-dong Puk-gu, Kwangju 500-712, South Korea. *Phone:* 82-62-970-2438 or 2475; *Fax:* 82-62-970-2434; *E-mail:* lee@kjist.ac.kr

particles (Ebert and Buttner, 1986; Gemci and Ebert, 1992).

Figure 1 is a sketch of a gravitational wet scrubber. The unit causes very little pressure loss, and can handle large volumes of gases. As the particle-laden gas flows upward, particles collide with liquid droplets sprayed across the flow passage, and then liquid droplets containing the particles settle to the bottom of the scrubber. It is known that gravitational wet scrubbers are generally not suitable for removing particles smaller than 1.0 μm. Scrubbers combined with electrical precipitation (Laitinen *et al.*, 1997) and modified scrubbers (Boll, 1973; Yung *et al.*, 1978; Fan *et al.*, 1988; Spink, 1988) had been suggested as a means to increase small particle removal efficiency. However, operational conditions of the gravitational wet scrubber, including droplet residence time, droplet size, and liquid-to-gas flow ratio, may play a role in removing particles much smaller than 1.0 μm in diameter. Although the gravitational wet scrubber is commonly used to remove particles from gas streams, the exact mechanisms involved are still not fully understood.

The present study seeks to help promote better understanding of the submicron particle-removing characteristics of gravitational wet scrubbers by exploring the effects of diffusion numerically. In addition, a comprehensive method of predicting not only the particle removal efficiency of gravitational wet scrubbers but also the particle size distribution properties, is described as an attempt to investigate the polydispersity effects of the particle size distribution on gravitational wet scrubbers. The proposed method takes into account diffusion in addition to impaction and interception. It is assumed that three collection efficiencies are additive, so the overall collection efficiency is described as the sum of all three. The approach also assumes that the size distribution of aerosol initially manifesting a lognormal distribution has three size parameters of a lognormal distribution function as the aerosol passes along the scrubber. A lognormal distribution function is described by three parameters. The three size distribution parameters, namely, the mean particle diameter, the geometric standard deviation, and the total particle number, are allowed to change during the calculation.

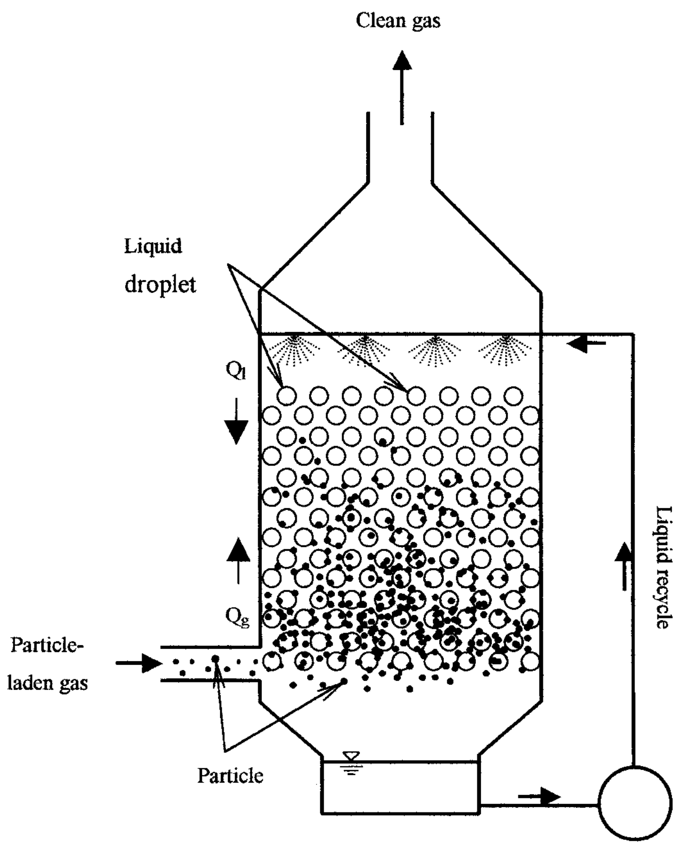

Figure 1. Schematic of a gravitational wet scrubber.

SINGLE DROPLET COLLECTION EFFICIENCY

Diffusion

Diffusion is the dominant collection mechanism for small particles in using wet scrubbers. Small particles attain a high diffusion coefficient because the diffusion coefficient is inversely proportional to size. Jung and Lee (1998) derived the following expression for diffusive collection efficiency of a single liquid sphere, which includes the effects of induced internal circulation inside a liquid droplet:

$$\eta_{\text{diff}} = 0.7\left\{\frac{4}{\sqrt{3}}\left(\frac{1-\alpha}{J+\sigma K}\right)^{\frac{1}{2}} Pe^{-\frac{1}{2}} + 2\left(\frac{\sqrt{3}\pi}{4Pe}\right)^{\frac{2}{3}}\left[\frac{(1-\alpha)(3\sigma+4)}{J+\sigma K}\right]^{\frac{1}{3}}\right\}, \quad (1)$$

where α is the packing density, σ is the viscosity ratio of water to air,

$$J = 1 - \frac{6}{5}\alpha^{\frac{1}{3}} + \frac{1}{5}\alpha^2,$$

$$K = 1 - \frac{9}{5}\alpha^{\frac{1}{3}} + \alpha + \frac{1}{5}\alpha^2, \text{ and}$$

$$Pe = \frac{DU}{D_{\text{diff}}}$$

is the Peclet number. For the diffusion coefficient, D_{diff}, appearing in the Peclet number, the following form is used:

$$D_{\text{diff}} = \frac{kTC}{3\pi\mu d_p}, \quad (2)$$

where k is the Boltzmann constant, T is the absolute temperature, μ is the viscosity of the air, d_p is the particle diameter, and C is the Cunningham slip correction factor. Lee and Liu (1980) used the following forms of the Cunningham slip correction factor based on the Knudsen-Weber equation:

$$C = \frac{2(1.664)\lambda}{d_p} \quad \text{for } Kn > 2.6 \text{ or } d_p < 0.05\ \mu\text{m}, \quad (3)$$

$$C = \frac{2.609\sqrt{2\lambda}}{d_p^{1/2}} \quad \text{for } 0.15 < Kn < 2.6 \text{ or } 0.05\ \mu\text{m} < d_p < 1.0\ \mu\text{m}, \quad (4)$$

where λ is the mean free path length of molecules, and Kn is the Knudsen number.

In the case of very small particles whose diameters are smaller than about 0.05 μm, by incorporating Equations (2) and (3), the Peclet number is expressed as

$$\text{Pe} = \frac{3\pi\mu DU}{2(1.664)kT\lambda}\ d_p^2, \quad (5)$$

where D is the water droplet diameter, and U is the velocity of water droplet relative to the tower. Substituting Equation (5) into Equation (1), we write

$$\eta_{\text{diff}} = \frac{2.8}{\sqrt{3}}\left(\frac{1-\alpha}{J+\sigma K}\right)^{\frac{1}{2}}\left(\frac{3\pi\mu DU}{2(1.664)kT\lambda}\right)^{-\frac{1}{2}} d_p^{-1} + 1.4\left(\frac{\sqrt{3}\pi}{4}\right)^{\frac{2}{3}}\left[\frac{(1-\alpha)(3\sigma+4)}{J+\sigma K}\right]^{\frac{1}{3}} \times \left(\frac{3\pi\mu DU}{2(1.664)kT\lambda}\right)^{-\frac{2}{3}} d_p^{-\frac{4}{3}}. \quad (6)$$

For particles in the intermediate size range of 0.05 μm to 1.0 μm in diameter, the correction factor is proportional to $(\lambda/d_p)^{1/2}$ as seen in Equation (4). Therefore, the following Peclet number is obtained:

$$Pe = \frac{3\pi\mu DU}{2.609kT\sqrt{2\lambda}}\ d_p^{\frac{3}{2}}. \quad (7)$$

With incorporation of Equations (7) and (1), Equation (8) is obtained:

$$\eta_{\text{diff}} = \frac{2.8}{\sqrt{3}}\left(\frac{1-\alpha}{J+\sigma K}\right)^{\frac{1}{2}}\left(\frac{3\pi\mu DU}{2.609kT\sqrt{2\lambda}}\right)^{-\frac{1}{2}} d_p^{-\frac{3}{4}} + 1.4\left(\frac{\sqrt{3}\pi}{4}\right)^{\frac{2}{3}}\left[\frac{(1-\alpha)(3\sigma+4)}{J+\sigma K}\right]^{\frac{1}{3}} \times \left(\frac{3\pi\mu DU}{2.609kT\sqrt{2\lambda}}\right)^{-\frac{2}{3}} d_p^{-1}. \quad (8)$$

Particle collection efficiency by diffusion is expected to decrease with increasing velocity of water droplet, as seen in Equations (6) and (8).

Interception

Even if the trajectory of a particle does not depart from the streamline, a particle may still be collected when the particle passes within one particle radius from the water droplet surface. Jung and Lee (1998) also derived the following collection efficiency of a single liquid sphere due to interception:

$$\eta_{\text{int}} = \frac{(1-\alpha)}{(J+\sigma K)}\left[\left(\frac{R}{1+R}\right) + \frac{1}{2}\left(\frac{R}{1+R}\right)^2(3\sigma+4)\right], \quad (9)$$

where

$$R\left(=\frac{d_p}{D}\right)$$

is the interception parameter. The efficiency due to direct interception is found to increase as the particle diameter and the packing density increase, and as the droplet diameter decreases. In general, the water droplet size is much larger than the particle size. By assuming

$$R \ll 1 \quad \text{or} \quad \frac{R}{1+R} \cong R,$$

Equation (9) can be estimated as

$$\eta_{\text{int}} = \left[\frac{(1-\alpha)}{(J+\sigma K)}\frac{1}{D}\right]d_p + \left[\frac{(1-\alpha)}{(J+\sigma K)}\frac{(3\sigma+4)}{2D^2}\right]d_p^2 \tag{10}$$

Interception is relatively independent of flow velocity for a given droplet as seen in Equation (10), and this characteristic can be contrasted with the flow-dependent characteristics of diffusion and impaction.

Impaction

Impaction is the dominant collection mechanism for particles whose diameters are larger than 5.0 μm in using wet scrubbers. The dimensionless parameter describing the impaction effect is the Stokes number, *Stk*, defined as

$$Stk = \frac{\rho_p d_p^2 (U_{sd} - U_{si})}{18\mu D}, \tag{11}$$

where ρ_p is the particle density, and U_{sd} and U_{si} are droplet falling velocity relative to the gas and settling velocity of particle, respectively. In many cases, U_{sd} is much larger than U_{si}. A large Stokes number implies a higher probability of collection by impaction, and vice-versa.

Licht (1988) calculated the impaction collection efficiency for particles in operating wet scrubbers. His expression for the collection efficiency due to impaction, η_{imp}, is as follows:

$$\eta_{\text{imp}} = \left(\frac{Stk}{Stk + 0.35}\right)^2. \tag{12}$$

This form, however, is not suitable for the moment equation used for a lognormal distribution, which will be discussed later. The collection efficiency due to impaction can be roughly estimated by assuming proportionality to $(Stk)^i$. The following equations have been found to approximate Equation (12):

$$\eta_{\text{imp}} = 3.4(Stk)^{\frac{9}{5}} \quad \text{for } Stk \le 0.5$$

and

$$\eta_{\text{imp}} = 1 \quad \text{for } Stk > 0.5, \tag{13}$$

or

$$\eta_{\text{imp}} = 3.4\left[\frac{\rho_p(U_{sd} - U_{si})}{18\mu D}\right]^{\frac{9}{5}} d_p^{\frac{18}{5}} \quad \text{for } Stk \le 0.5$$

and

$$\eta_{\text{imp}} = 1 \quad \text{for } Stk > 0.5. \tag{14}$$

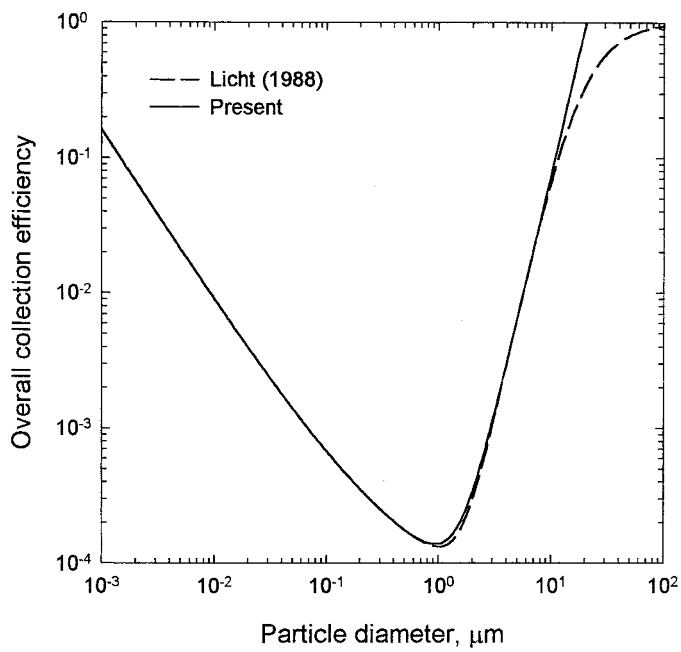

Figure 2. Overall collection efficiency as approximated in the present study compared with that of Licht (1988).

The overall collection efficiency, which accounts for particle diffusion, interception, and inertial impaction, as estimated by a combination of Equations (1), (9), and (14) is compared to collection efficiency due exclusively to impaction as given by Equation (12) in Fig. 2. It is seen from this comparison that the results closely resemble each other until particle diameter is around 10 μm. In general, for aerosol particles whose diameters are larger than 15 μm, the collection efficiency due to impaction approaches unity (Wark and Warner, 1981). The modified equation of the collection efficiency in impaction region explains this phenomenon well. There exist some discrepancies between Licht's (1988) prediction and the present one as the collection efficiency goes to unity, because of the approximations made.

CHANGE IN SIZE DISTRIBUTION

A method based on the integration of lognormal function moments is employed with the single water droplet collection efficiency for gravitational wet scrubbers. It is assumed that no loading occurs on the water droplet, and that the particles adhere to the droplet surface upon contact. This method likewise assumes that the size distribution of aerosol initially having a lognormal distribution is described with three size parameters of a lognormal distribution function as it passes along the wet scrubber. The three size distribution parameters, namely, the mean particle diameter, the geometric standard deviation, and the total particle number, are allowed to vary during the calculation. This type of representation is widely used in characterization of time-dependent size distribution of particles in the modeling of aerosols and in comparing experimental data.

$d_p < 0.05\ \mu$m

In the case of particles whose diameters are smaller than about 0.05 μm, the effects of interception and impaction are negligible. The overall collection efficiency, $\eta_{\text{diff}} + \eta_{\text{int}} + \eta_{\text{imp}}$, can be approximated by assuming $\eta_{\text{int}} \cong \eta_{\text{imp}} \cong 0$:

$$\eta_{\text{total}} = \eta_{\text{diff}} = \xi_1 d_p^{-1} + \xi_2 d_p^{-\frac{4}{3}}, \qquad (15)$$

where

$$\xi_1 = \frac{2.8}{\sqrt{3}}\left(\frac{1-\alpha}{J+\sigma K}\right)^{\frac{1}{2}}\left(\frac{3\pi\mu DU}{2(1.664)kT\lambda}\right)^{-\frac{1}{2}}, \text{ and}$$

$$\xi_2 = 1.4\left(\frac{\sqrt{3}\pi}{4}\right)^{\frac{2}{3}}\left[\frac{(1-\alpha)(3\sigma+4)}{J+\sigma K}\right]^{\frac{1}{3}} \times \left(\frac{3\pi\mu DU}{2(1.664)kT\lambda}\right)^{-\frac{2}{3}}.$$

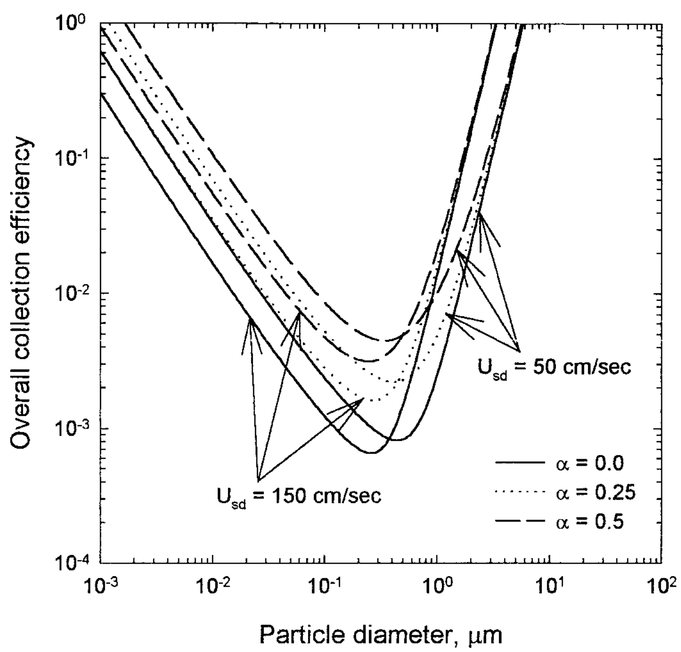

Figure 3. Overall collection efficiency for different droplet falling velocities and same droplet size (D = 0.1 mm).

The following form of the total particle collection taking place at a particular time was used by Licht (1988):

$$\frac{\partial n}{\partial t} = -\frac{3}{2}\frac{Q_1(U_{sd} - U_{si})}{Q_g D}(\eta_{\text{total}})n = -A(\eta_{\text{total}})n, \quad (16)$$

where

$$A = \frac{3Q_1(U_{sd} - U_{si})}{2Q_g D}.$$

With incorporation of Equation (15), Equation (16) becomes

$$\frac{\partial n}{\partial t} = -A(\xi_1 d_p^{-1} + \xi_2 d_p^{-\frac{4}{3}})n. \quad (17)$$

Introducing the representation of the moment equation for a lognormal distribution, the ith moment, M_i, is defined as

$$M_i = \frac{N}{\sqrt{2\pi}\ \ln \sigma_g}\int_0^\infty d_p^i \exp\left[-\frac{\ln^2(d_p/d_{pg})}{2\ \ln^2 \sigma_g}\right]\frac{1}{d_p}\,dd_p, \quad (18)$$

where i is an arbitrary real number. The following relation exists among the moments of a lognormal function:

$$M_i = M_0 \cdot d_{pg}^i \cdot \exp\left(\frac{i^2}{2}\ \ln^2 \sigma_g\right). \quad (19)$$

Solving Equation (19) for d_{pg} and σ_g in terms of M_0, M_1, and M_2, the two following equations are obtained:

$$d_{pg} = \frac{M_1^2}{M_0^{3/2} M_2^{1/2}},$$

and

$$\sigma_g = \exp\left[\ln\left(\frac{M_0 M_2}{M_1^2}\right)\right]^{\frac{1}{2}}. \quad (20)$$

By incorporating Equations (17) and (18), Equations (21), (22), and (23) are obtained for $i = 0$, 1, and 2, respectively:

$$\frac{dM_0}{dt} = -A\left(\xi_1 M_{-1} + \xi_2 M_{-\frac{4}{3}}\right)$$

$$= -A\left(\xi_1 M_0^3 M_1^{-3} M_2^1 + \xi_2 M_0^{\frac{35}{9}} M_1^{-\frac{40}{9}} M_2^{\frac{14}{9}}\right), \quad (21)$$

$$\frac{dM_1}{dt} = -A\left(\xi_1 M_0 + \xi_2 M_{-\frac{1}{3}}\right)$$

$$= -A\left(\xi_1 M_0^1 + \xi_2 M_0^{\frac{14}{9}} M_1^{-\frac{7}{9}} M_2^{\frac{2}{9}}\right), \quad (22)$$

$$\frac{dM_2}{dt} = -A\left(\xi_1 M_1 + \xi_2 M_{\frac{2}{3}}\right)$$

$$= -A\left(\xi_1 M_1^1 + \xi_2 M_0^{\frac{2}{9}} M_1^{\frac{8}{9}} M_2^{-\frac{1}{9}}\right), \quad (23)$$

$$d_p > 0.05\ \mu\text{m}$$

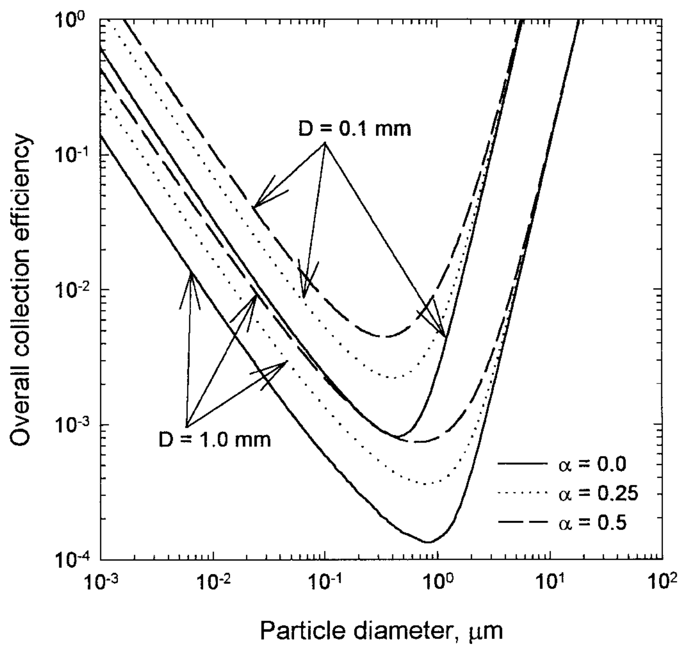

Figure 4. Overall collection efficiency for different droplet sizes and uniform droplet falling velocity (U_{sd} = 50 cm/s).

In the case of particles whose diameters are larger than 0.05 μm, the overall collection efficiency is defined as

$$\eta_{\text{total}} = \eta_{\text{diff}} + \eta_{\text{int}} + \eta_{\text{imp}} = \xi_3 d_p^{-\frac{3}{4}} + \xi_4 d_p^{-1} + \xi_5 d_p + \xi_6 d_p^2 + \xi_7 d_p^{\frac{18}{5}}, \quad (24)$$

where

$$\xi_3 = \frac{2.8}{\sqrt{3}}\left(\frac{1-\alpha}{J+\sigma K}\right)^{\frac{1}{2}}\left(\frac{3\pi\mu DU}{2.609kT\sqrt{2}\lambda}\right)^{-\frac{1}{2}},$$

$$\xi_4 = 1.4\left(\frac{\sqrt{3}\pi}{4}\right)^{\frac{2}{3}}\left[\frac{(1-\alpha)(3\sigma+4)}{J+\sigma K}\right]^{\frac{1}{3}} \times \left(\frac{3\pi\mu DU}{2.609kT\sqrt{2}\lambda}\right)^{-\frac{2}{3}},$$

$$\xi_5 = \left[\frac{(1-\alpha)}{(J+\sigma K)}\,\frac{1}{D}\right],$$

$$\xi_6 = \left[\frac{(1-\alpha)}{(J+\sigma K)}\,\frac{(3\sigma+4)}{2D^2}\right], \text{ and}$$

$$\xi_7 = 3.4\left[\frac{\rho_p(U_{sd}-U_{si})}{18\mu D}\right]^{\frac{9}{5}}$$

By incorporating Equation (24), Equation (16) becomes

$$\frac{\partial n}{\partial t} = -A\left(\xi_3 d_p^{-\frac{3}{4}} + \xi_4 d_p^{-1} + \xi_5 d_p + \xi_6 d_p^2 + \xi_7 d_p^{\frac{18}{5}}\right)n. \quad (25)$$

Following the same derivation used in the case of $d_p < 0.05$ μm, the following three simultaneous equations are obtained:

$$\frac{dM_0}{dt} = -A\left(\xi_3 M_{-\frac{3}{4}} + \xi_4 M_{-1} + \xi_5 M_1 + \xi_6 M_2 + \xi_7 M_{\frac{18}{5}}\right)$$
$$= -A\left(\xi_3 M_0^{\frac{77}{32}} M_1^{-\frac{66}{32}} M_2^{\frac{21}{32}} + \xi_4 M_0^3 M_1^{-3} M_2^1 + \xi_5 M_1^1 + \xi_6 M_2^1 + \xi_7 M_0^{\frac{52}{25}} M_1^{-\frac{144}{25}} M_2^{\frac{117}{25}}\right), \quad (26)$$

$$\frac{dM_1}{dt} = -A\left(\xi_3 M_{\frac{1}{4}} + \xi_4 M_0 + \xi_5 M_2 + \xi_6 M_3 + \xi_7 M_{\frac{23}{5}}\right)$$
$$= -A\left(\xi_3 M_0^{\frac{21}{32}} M_1^{\frac{14}{32}} M_2^{-\frac{3}{32}} + \xi_4 M_0^1 + \xi_5 M_2^1 + \xi_6 M_0^1 M_1^{-3} M_2^3 + \xi_7 M_0^{\frac{117}{25}} M_1^{-\frac{299}{25}} M_2^{\frac{207}{25}}\right), \quad (27)$$

$$\frac{dM_2}{dt} = -A\left(\xi_3 M_{\frac{5}{4}} + \xi_4 M_1 + \xi_5 M_3 + \xi_6 M_4 + \xi_7 M_{\frac{28}{5}}\right)$$
$$= -A\left(\xi_3 M_0^{-\frac{3}{32}} M_1^{\frac{30}{32}} M_0^{\frac{5}{32}} + \xi_4 M_1^1 + \xi_5 M_0^1 M_1^{-3} M_2^3 + \xi_6 M_0^3 M_1^{-8} M_2^6 + \xi_7 M_0^{\frac{207}{25}} M_1^{-\frac{504}{25}} M_2^{\frac{322}{25}}\right). \quad (28)$$

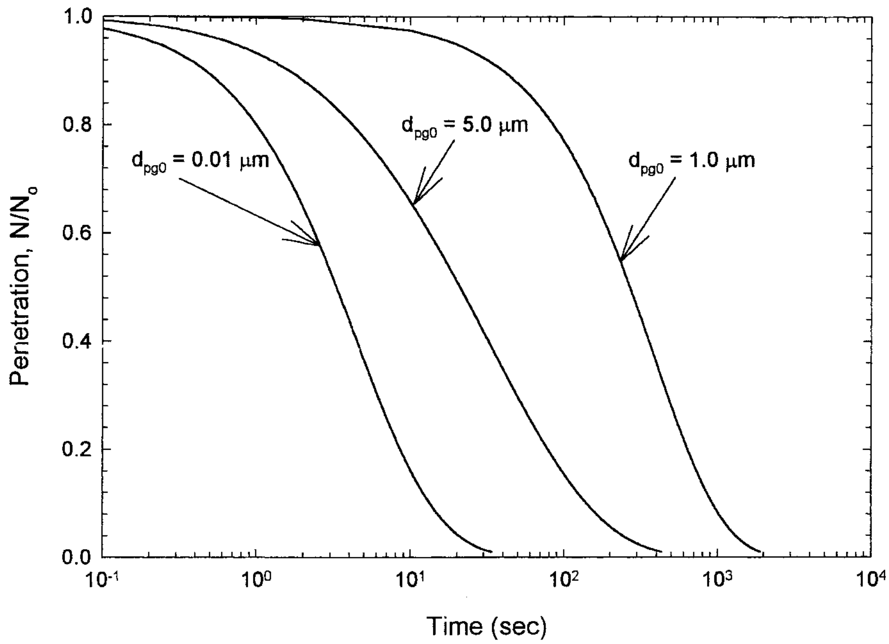

Figure 5. Penetration of particles in different geometric mean diameters.

Because we have three unknowns and three equations, Equations (21) through (23) or Equations (26) through (28) can be directly solved as a function of the time, t, using any standard solution package for first-order simultaneous ordinary differential equations. It is noted that the present method covers the entire range of particle size, from zero to infinite, as mathematically reflected by a lognormal distribution function.

RESULTS AND DISCUSSION

The overall collection efficiency of gravitational wet scrubbers can be changed when operational conditions such as velocity of falling droplet, droplet size, and liquid-to-gas flow ratio are varied. Figure 3 shows that overall collection efficiency curves significantly move to the right as velocity of falling droplet decreases. This means that a decrease in the velocity of a falling droplet can help collect small particles, but it prevents large particles from being captured. This can be easily understood from the general idea that particle collections by diffusion and by impaction increase with decreasing and with increasing flow velocity, respectively. Droplet size plays a significant role in the scrubber collection efficiency. One of the most important design implications of a wet scrubber is the droplet size of water. To achieve better removal efficiency of fine particles as well as the overall removal efficiency, it is suggested to decrease the droplet size of water. Figure 4 shows that particle collection efficiencies are enhanced for the entire particle size range as droplet size decreases.

From Figs. 3 and 4, one can recognize that the collection efficiencies show the U-shaped curves with a minimum in the region of approximately 1.0 μm in particle diameter, which is referred to as the intermediate region. The penetration of particles as a function of time was calculated with three polydispersed aerosols for comparison. Their geometric mean diameters were 0.01, 1.0, and 5.0 μm, respectively, but standard deviations were the same at 1.5. Figure 5 shows that in the case of aerosol with $d_{pg0} = 1.0$ μm in the intermediate region, all of the particles are not removed until the aerosol with $d_{pg0} = 0.01$ μm in the diffusion-dominant region is nearly removed. In the case of the geometric mean particle diameter of 0.01 μm, the diffusion mechanism is dominant, while for the case of geometric mean diameter of 1.0 μm, there exists a region where the interception and the diffusion are minimum. The minimum is called the most penetrating particle size region. Thus, particles having a diameter of 0.01 μm are removed faster than those with a diameter of 1.0 μm, for example. The figure also shows that at low droplet falling velocity of 40 cm/s, aerosol in the diffusion-dominant region is removed faster than aerosol with $d_{pg0} = 5.0$ μm in the impaction-dominant region.

The three size distribution parameters of aerosol may change in the course of scrubbing. To obtain information on them, the three ordinary differential equations shown

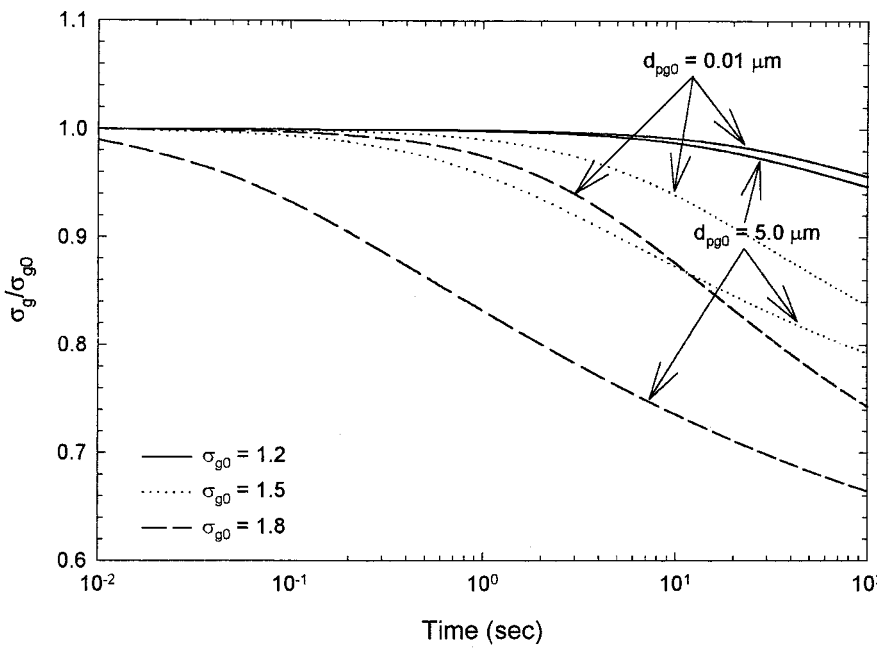

Figure 6. Geometric standard deviation of aerosol particle size distribution in the diffusion-dominant region ($d_{pg0} = 0.01$ μm) and in the impaction-dominant region ($d_{pg0} = 5.0$ μm).

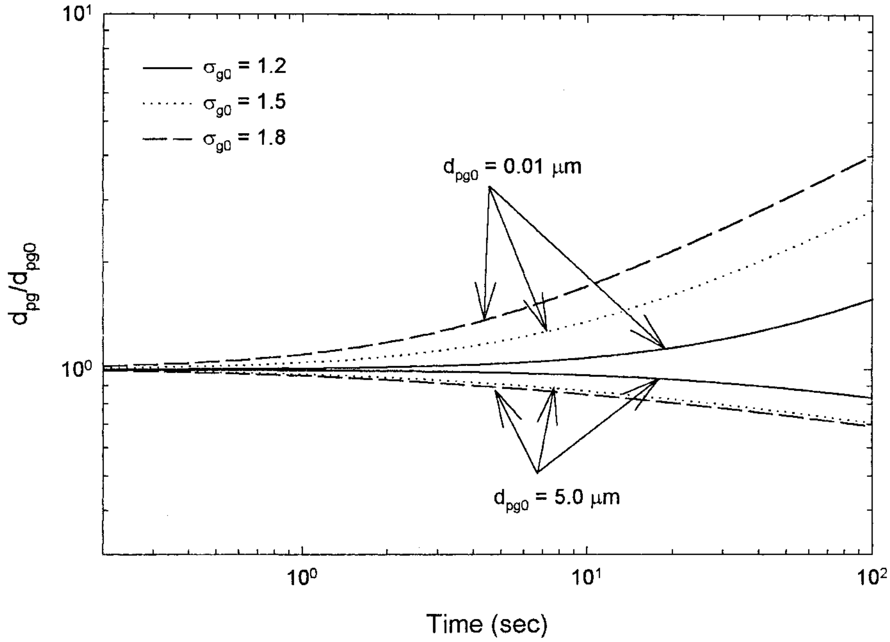

Figure 7. Geometric mean diameter of aerosol particle size distribution in the diffusion-dominant region ($d_{pg0} = 0.01$ μm) and in the impaction-dominant region ($d_{pg0} = 5.0$ μm).

in Equations (21) through (23) or Equations (26) through (28) were solved numerically. Figures 6 and 7 are the geometric standard deviation and geometric mean diameter, respectively, as calculated. All of the geometric standard deviations for polydispersed aerosols decrease in time, but the standard deviation of aerosol in the impaction-dominant region decreases at a higher rate than that in the diffusion-dominant region. Figure 7 shows two

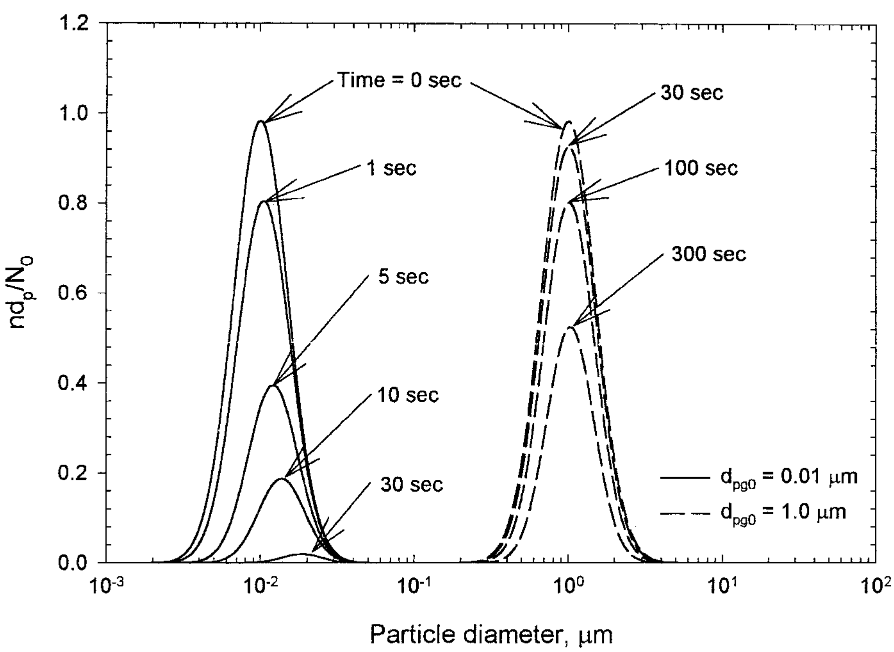

Figure 8. Particle size distribution of aerosols in the diffusion-dominant region ($d_{pg0} = 0.01$ μm) and in the intermediate region ($d_{pg0} = 1.0$ μm).

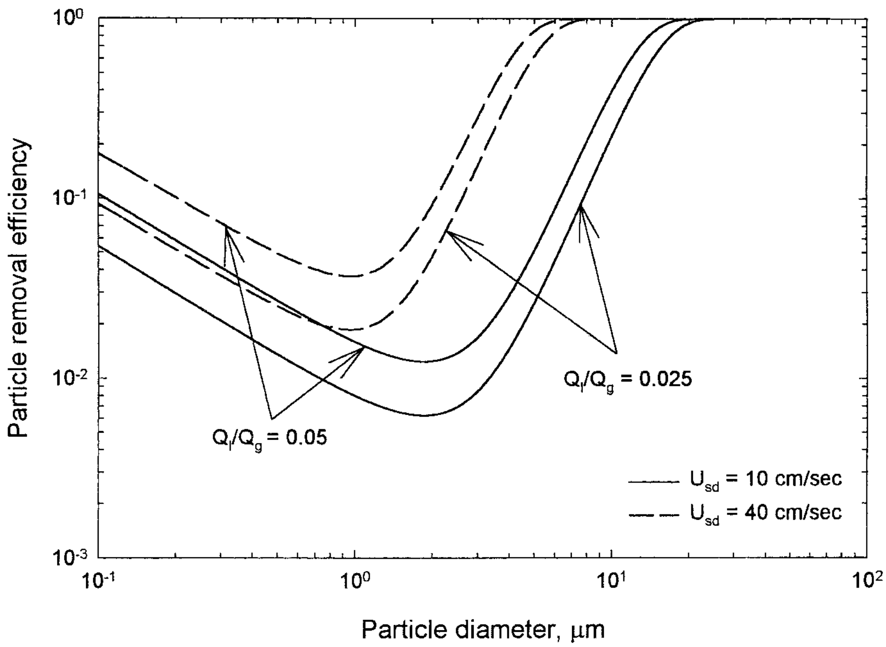

Figure 9. Particle removal efficiency as a function of particle diameter.

different tendencies of geometric mean diameters. The mean diameter of aerosol in the diffusion-dominant region increases in the course of scrubbing, whereas in the impaction-dominant region it decreases. This is clearly because the overall collection efficiency curve is parabolic, as mentioned above. That means the collection efficiencies of aerosols both in the diffusion- and in the impaction-dominant regions are higher than that in the intermediate region. Figure 8 is the particle size distribution showing the decrease in the total number of aerosol in the diffusion-dominant region at a higher rate compared with aerosol in the intermediate region.

The liquid-to-gas flow ratio is of basic importance in the performance of all kinds of wet scrubbers. Figure 9 is the particle removal efficiency as a function of particle diameter, which does not exhibit the usual S-shaped curve starting at zero and increasing steadily and consistently. Leith *et al.* (1985) reported the similar particle removal curve for venturi scrubber, which seemed to involve diffusive transport of dust to washing droplets. It is believed that the high efficiency in removing submicron particles is due to the diffusion of particles to droplets. A high liquid-to-gas flow ratio can likewise help remove particles (Licht, 1988). Figure 9 also shows that the efficiency increases as the liquid-to-gas flow ratio increases.

Contrary to the general idea, this study shows that in optimum operational conditions such as low droplet falling velocity, small droplet size, and high liquid-to-gas flow ratio, the gravitational wet scrubber has sufficient ability to remove particles whose diameters are much smaller than 1.0 μm. It may be required to compare the present results with previous experimental results for evaluation. However, few efforts have been made to test the performance of gravitational wet scrubbers. There has been no comprehensive experimental test done primarily because of the lack of adequate experimental technique (Perry and Green, 1984). To remove fine particles, the droplet velocity and the droplet size of water should be decreased. Occasionally, the scrubbers in operation may be operated outside their operating conditions. To show the fine particle removal by diffusion, the droplet velocity in the present study was made slightly out of normal operating conditions, but not by much. Thus, it is believed that the economical operation of the scrubbers can be required by proper adjustment of droplet size, droplet velocity, and the liquid-to-gas flow ratio. Additional systematic analyses for economical design and optimum operation remain as future study.

CONCLUSIONS

In this paper, a comprehensive method that can predict the particle removal efficiency of gravitational wet scrubbers and the particle size distribution properties has been described to investigate the polydispersity effects of particle size distribution. The conclusions drawn from the present study can be summarized as follows.

1. The droplet residence time plays a significant role in the gravitational wet scrubber efficiency. Longer duration can help remove small particles, whereas large particles collection efficiency decreases.
2. Liquid droplet size and liquid-to-gas flow ratio are important in determining the particle removal efficiency of gravitational wet scrubbers. The overall collection efficiency is enhanced in the entire particle size range either as droplet size decreases, or as liquid-to-gas flow ratio increases.
3. Contrary to the conventional idea that gravitational wet scrubbers are not suitable for removing particles smaller than 1.0 μm, this study shows that given optimum operational conditions, the gravitational wet scrubber has a sufficient ability to remove particles much smaller than 1.0 μm in diameter. It is believed that this work represents the first study to quantitatively address importance of the diffusion effects on gravitational wet scrubbers, as well as the polydispersity effects of particle size distribution.
4. As aerosols pass through the gravitational wet scrubber, geometric standard deviations of size distribution for polydispersed aerosols decrease. The geometric mean diameter of aerosol in the diffusion-dominant region increases, whereas that in the impaction-dominant region decreases.
5. There has not been a comprehensive experimental study conducted primarily because of lack of adequate experimental techniques. Thus, the experimental verification of gravitational wet scrubber remains for future study.

This study focused on the understanding of the basic concept of removing particles scavenged by gravitational wet scrubbers. Thus, more complicated factors such as particle wetting, coalescence of fine droplets, and generation of fine particles inside the scrubber were not considered. The significance of the present work is quantification of the overall wet scrubbing efficiency and change in the size distribution of the aerosol being scrubbed. It is expected that the information given here will be useful for many scrubber applications in relevant measurements.

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NOMENCLATURE

A	constant, defined in Equation (16)
C	Cunningham slip correction factor (dimensionless)
d_p	diameter of particle (cm)
d_{pg}	geometric mean particle diameter (cm)
d_{pg0}	geometric mean particle diameter at $t = 0$ (cm)
D	diameter of water droplet (cm)
D_{diff}	diffusion coefficient (cm^2/s)
i	arbitrary real number
J	hydrodynamic factor, $J = 1 - \frac{6}{5}\alpha^{1/3} + \frac{1}{5}\alpha^2$
k	Boltzmann constant (g cm^2/s^2/K)
K	hydrodynamic factor, $K = 1 - \frac{9}{5}\alpha^{1/3} + \alpha - \frac{1}{5}\alpha^2$
Kn	Knudsen number (dimensionless)
M_i	ith moment of lognormal size distribution function
n	particle number concentration (particles/cm^3)
N	total number of particles in distribution (particles)
N_0	total number of particles at $t = 0$ (particles)
Pe	Peclet number, $Pe = \frac{DU}{D_{\text{diff}}}$ (dimensionless)
Q_g, Q_l	gas and liquid flow rates (cm^3/s)
R	interception parameter, $R = \frac{d_p}{D}$ (dimensionless)
Stk	Stokes number, $Stk = \frac{\rho_p d_p^2 (U_{sd} - U_{si})}{18\mu D}$ (dimensionless)
T	absolute temperature (K)
t	time (s)
U	velocity of water droplet relative to the tower (cm/s)
U_{sd}	droplet falling velocity relative to the gas (cm/s)
U_{si}	settling velocity of particle (cm/s)

Greek Letters

α	volume fraction, solidity or packing density
η_{diff}	single water droplet collection efficiency due to diffusion

η_{imp} single water droplet collection efficiency due to impaction
η_{int} single water droplet collection efficiency due to interception
η_{total} overall collection efficiency, $\eta_{total} = \eta_{diff} + \eta_{int} + \eta_{imp}$
λ mean free path length of molecules (cm)
μ viscosity of air (g/cm/s)
ρ_p density of particle (g/cm^3)
σ viscosity ratio of water to air
σ_g geometric standard deviation
σ_{g0} geometric standard deviation at $t = 0$
ξ_i constant

Subscripts

diff diffusion
imp impaction
int interception

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