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Development and application of a novel swirl cyclone scrubber(2) Theoretical

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ABSTRACT

The swirl cyclone scrubber analyzed in this paper is a novel aerosol filtering device in which a uniflow cyclone and a scrubber are combined. Systematic experiments showed that the swirl scrubber is a promising device that has minimal installation, operational, and maintenance costs. In this article, theoretical analyses are developed for the swirl cyclone scrubber. The dependency of particle collection efficiency on the design and operating parameters observed by experiments is explained using a theoretical parameterization to provide guidelines for optimal design and operation of the device. Discussion on possible variations of the swirl cyclone scrubber is also presented based on the theoretical parameterization developed.

1. Introduction

Cyclones are very useful pre-cleaning devices that can effectively remove airborne particles larger than 10 μm in their aerodynamic diameter. Cyclones are widely used because of their low costs of installation, operation and maintenance. Their particle collection efficiency, however, rapidly decreases with decreasing particle size [1,2]. High collection efficiency for small particles can only be obtained with significant pressure drop and operation cost increase. Contamination of inner wall by collection of adhesive particulates such as tars is another disadvantage of cyclones.

Wet scrubbers have been widely used for removing gaseous and particulate air pollutants with significantly reduced risks of fire, explosion and erosion [3–5]. Conventional wet scrubbers often suffer from clogging and fouling problems by salt formation at the tip, the inside and outside of the nozzles, the tubes and the walls of scrubbers. Another drawback of conventional wet scrubbers is high pressure drop resulting from the improvement of collection efficiency [6].

Cyclone scrubbers have been developed to enhance the particle removal efficiency of conventional cyclones by adding the wet scrubbing effect. Although cyclone scrubbers have shown better particle removal performance than conventional cyclones [7,8], they still share the same problems with conventional cyclones such as contamination by adhesive particles.

We have developed a novel aerosol filtering device, the swirl cyclone scrubber (swirl scrubber hereafter) that mainly consists of a cyclone and a swirl scrubber with a rod impact plate and swirl plates (Fig. 1), to overcome the many drawbacks of conventional cyclones and wet scrubbers. The lower zone of the device is a uniflow tangential-inlet cyclone. Aerosol particles entering the device are collected on the cyclone wall by centrifugal force. The upper zone was designed to be a wet scrubber in which water fed through a nozzle impinges on the impaction plate, generating water spray. Particles are removed by collisions with drops from the spray. Water drops deposited on the scrubber wall form a water film flowing down along the wall, which provides more adhesive deposition surface for particles collected by centrifugal force in the cyclone zone. The film also prevents contamination of the scrubber wall by sticky or corrosive particulates. Placed between the lower and upper zones is a swirl plate that not only sustains the swirling air flow, but also maintains a thick water layer on it. This, which is the most important difference from other cyclone scrubbers, provides another chance for aerosol particles to be filtered when particle-laden air passes through the water layer, a process called pool scrubbing. For more detailed information on the design and operation of the swirl scrubber, one can refer to the sister paper of this article [9].

Systematic experiments showed that the swirl scrubber is a promising air filtering device with minimal installation, operational, and maintenance costs [9]. It is expected to be particularly

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Nomenclature

a	height of the cyclone inlet
b	width of the cyclone inlet
C_c	Cunningham slip correction factor
d_p	particle diameter
d_{50}	cut-diameter (the diameter of a particle whose collection efficiency is 50%)
D_c	cyclone body diameter
D_d	water drop diameter
E_{dif}	collision efficiencies due to Brownian diffusion
E_{imp}	collision efficiencies due to inertial impaction
E_{int}	collision efficiencies due to interception
g	gravitational acceleration
H	cyclone body height
H_p	thickness of the water layer
k_B	Boltzmann constant
N	number of particles in the bubble
N_d	concentration of water drops
N_e	effective number of turns made in the cyclone
R_b	radius of the bubble
Re	Reynolds number
t	time
t_r	residence time of the wet scrubbing zone
T	absolute temperature
U_d	falling velocity of water drops
v_i	flow velocity at the cyclone inlet
V_b	rising velocity of the bubble
z	vertical coordinate

Greek symbols

α	volume fraction of water drops
β	slope parameter
η	collection efficiency of the swirl scrubber
η_c	collection efficiency by cyclone
η_p	collection efficiency by pool scrubbing
η_s	collection efficiency by pool and wet scrubbing
η_w	collection efficiency by wet scrubbing
κ	aerosol removal efficiency
λ	mean free path length of air molecules
μ	air viscosity
μ_L	viscosity of water
ρ_L	density of water
ρ_p	particle density
σ_s	surface tension of water

useful when one needs to control adhesive and/or corrosive particulates. One possible drawback of the swirl scrubber is relatively large water consumption and the need of waste-water treatment. Recycling of water, however, is expected to be able to reduce this problem significantly. In this article, theoretical analyses are developed for the swirl scrubber. The dependency of particle collection efficiency on the design and operating parameters observed by experiments are explained theoretically to provide guidelines for optimal design and operation of the device.

2. Experiment

The experiment for development and evaluation of the swirl scrubber is briefly summarized here although the detailed information is reported in the sister paper [9].

The swirl scrubber (Figs. 1 and 2) consists mainly of a cyclone, swirl plates, a scrubber, feeding and circulation devices of scrubbing medium, and demister. A gas stream containing particulates enters the cyclone with tangential direction through the vane attached on the bottom part of the swirl scrubber. After the gas stream passes through the cyclone zone, it enters the pool scrubbing zone, composed of the swirl plate and water layer on it, and then experiences the wet scrubber zone. The scrubbing medium circulates with significant swirl on the swirl plate zone forming a water layer whose depth depends upon the volumetric flow rate of the medium fed into the scrubber and the tilting angle of the swirl plates. The gases and particles that have passed through the swirl plate meet the water layer with a depth ranging from 5 to 20 cm. While the gas bubbles rise up through the water layer, particles come in contact with water by inertial impaction, gravitational settling, and Brownian diffusion and collected. Gases are collected by absorption and adsorption. The tilting angle, number, size, and surface area of the swirl plates are adjusted to obtain optimum removal effects with low pressure drop. The swirl plate zone and the water layer on it are the most important parts of the swirl scrubber system to improve collection efficiency of gases and small particles. In order to build a proper water layer circulating on the swirl plate zone, it is necessary to adjust the swirl plate angle and the volumetric flow rate of the scrubbing medium. The gases and particles that have passed through the pool scrubbing zone meet the spray of the scrubbing medium produced by direct impaction with the impact plate located in the center of the scrubber. The spray characteristics affect the collection efficiency of the gases and particles. The size and amount of the spray depends upon the volumetric injection (feed) rate and the injection nozzle size.

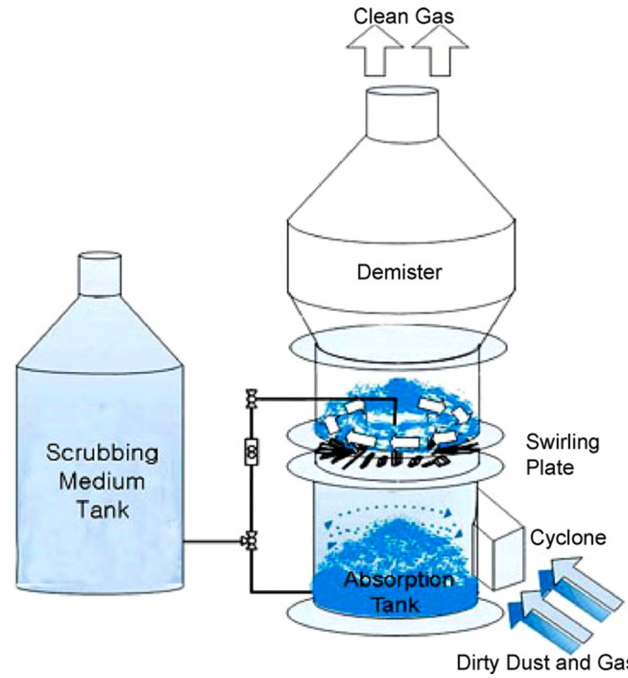

Fig. 1. A schematic of the novel swirl cyclone scrubber (NSCS).

Fig. 2 shows a schematic of the system evaluating the performance of the swirl scrubber. The dust feeder (Micro Feeder, Model IMF-2, SIBATA Scientific Technology Ltd.) generated fly ash particles ranging from 0.1 to larger than 10.0 μm in aerodynamic diameter. The produced particles were sent into the swirl scrubber with a feed velocity of 8.9 m/s, i.e., with a volumetric flow rate of 16.8 m^3/min. Particle collection efficiencies were computed by the difference between particle number concentrations measured at the inlet and

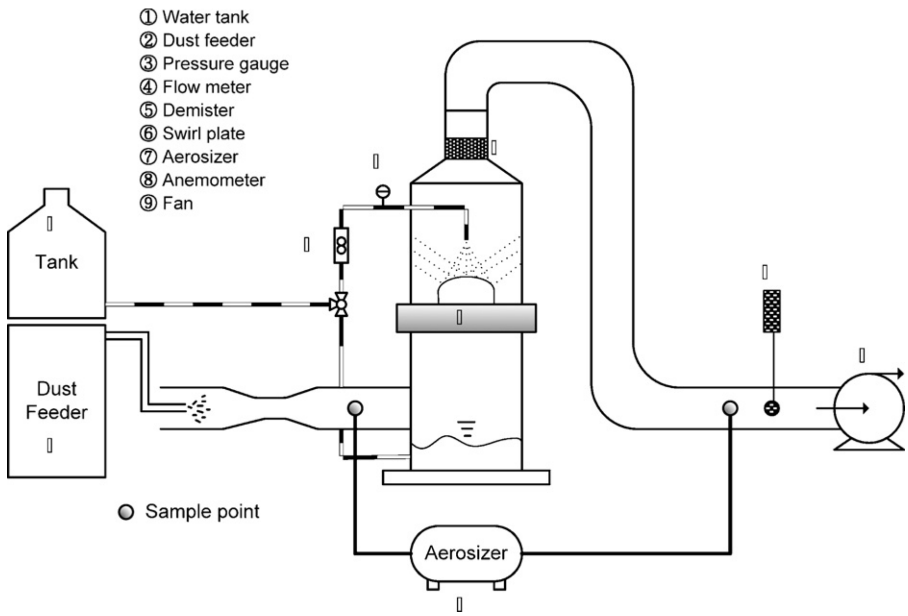

Fig. 2. A schematic of the system measuring the particle collection efficiency of the swirl scrubber.

at the outlet using the aerosol measurement system (Aerosizer, Model Mach II and LD, API).

To determine the average collection efficiency, seven repeated measurements were conducted for a given experimental set. The collection efficiencies of the test particles were obtained as a function of the swirl plate angle (15°, 30° and 45°), the supply pressure (0.7, 1.6, 2.0, 3.0 and 4.0 kgf/cm^2), the volumetric flow rate of scrubbing medium (7.5–8.0, 17.5, 30.0 and 34.0 L/min), which correspond to the liquid-to-gas ratio of 0.447–2.03 L/m^3, the size of the generated particles, and the nozzle size (Ø 2.0, 7.5, 9.0 and 15.0 mm). Additional collection effect of particles by adding the impaction plate (round rod) in the upper part of scrubber system was also examined. Finally, the particle collection efficiency by the cyclone alone (without scrubbing), by the scrubber alone (without cyclone effect), and by the whole swirl scrubber system was identified.

The particle collection efficiency increased with decreasing swirl plate angle, increasing pressure of scrubbing medium at the nozzle tip, and increasing volumetric flow rate of the scrubbing medium. The system with an addition of a round-shaped rod impaction plate in the place between the nozzle tip and the swirl plate zone showed an additional improvement in the overall collection efficiency, in particular, of particles less than 2.5 μm in aerodynamic diameter. The optimized NSCS system had a significantly high and stable particle collection efficiency, negligible pressure drop ranging from 110 to 120 mmH$_2$O, cheap building costs, and low operation and maintenance costs. Also, the NSCS system successfully solved the clogging problems inside collection devices by salt formation and/or sticky particulates. Therefore, the swirl scrubber system is expected to be a very useful device for particle control in many industrial scale applications.

3. Particle collection theory

The swirl scrubber analyzed in this article can be regarded as a serial combination of a uniflow cyclone, a pool scrubber, and a wet scrubber (Fig. 1). When particle collection by those three devices takes place independently in series, the combined collection efficiency can be expressed as

$$\eta = 1 - (1 - \eta_c)(1 - \eta_p)(1 - \eta_w). \quad (1)$$

3.1. Cyclone

In the cyclone zone of the swirl scrubber, incoming air spirals upward from the tangential inlet along the device wall. During transport along the spiral air flow, particles with large inertia deviate from the streamline and are collected on the wall due to the centrifugal force.

Two different theories have widely been used for particle collection efficiency of cyclones: the static particle approach [10] and the time-of-flight approach [11]. Since the static particle approach and many other cyclone theories available in the literature [12,13] can be applied only for reverse-flow cyclones, we use the time-of-flight approach suggested by Lapple [11] in this study. In this approach, under the assumption that the radial velocity and acceleration of particles are zero, the probability for a particle to reach the wall before it exits the cyclone is calculated. The cut-diameter, the diameter of a particle whose collection efficiency is 50%, is then expressed as

$$d_{50} = \sqrt{\frac{9\mu b}{2\pi \rho_p v_i N_e}}. \quad (2)$$

Assuming no mixing in the cyclone, N_e is approximated to be H/a in this study. Given the cut-diameter, the collection efficiency can be expressed as a function of particle diameter, d_p:

$$\eta_c = \frac{1}{1 + (d_{50}/d_p)^{\beta}}. \quad (3)$$

The slope parameter β depends on the cyclone design and was suggested experimentally by Iozia and Leith [14] to be

$$\ln(\beta) = 0.62 - 0.87\ln(d_{50}\,(\text{cm})) + 5.21\ln\left(\frac{ab}{D_c^2}\right) + 1.05\ln^2\left(\frac{ab}{D_c^2}\right). \quad (4)$$

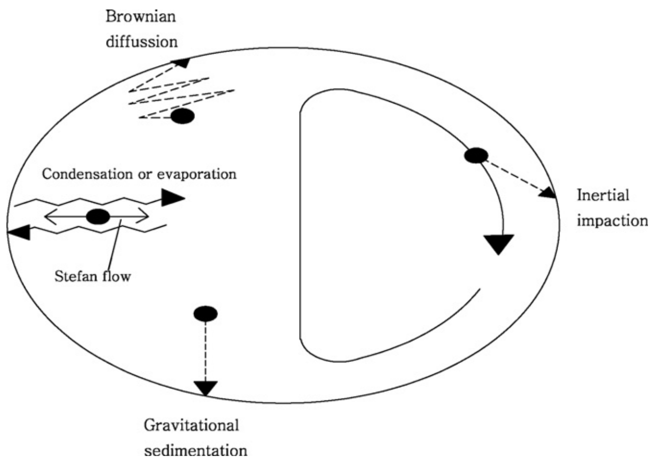

Fig. 3. Particle removal mechanisms of pool scrubbing.

3.2. Pool scrubbing

In a swirl scrubber, water drops generated by the nozzle-impaction plate system deposit onto and flow down along the scrubber wall. However, they do not pass through the swirl plate easily; the tilted structure of the plate results in a thick water layer on the plate, which functions as a pool scrubber.

When particle-laden air passes up through a water layer, a number of small air bubbles are formed. In a process called pool scrubbing, aerosol particles entrained in air bubbles rising through the water collect on the bubble surface due to various transport mechanisms including Brownian diffusion, gravitational sedimentation, and inertial impaction. Fig. 3 illustrates the principle of particle collection in a rising bubble. Brownian diffusion controls the removal rate for small particles, whereas gravitational sedimentation and inertial impaction play significant roles for large particles. If significant evaporation or condensation takes place, Stefan flow can impose an additional aerodynamic impact on the motion of particles. In this study, this effect is neglected.

Fuchs [15] was the first to attempt a theoretical explanation for the experimental observations of pool scrubbing of aerosol particles. He derived the aerosol removal efficiencies due to Brownian diffusion, inertial impaction, and gravitational sedimentation by assuming that particles are homogeneously distributed in each bubble. According to his theory, by assuming that the various deposition mechanisms are uncoupled and additive, the particle concentration decay in a spherical bubble can be expressed as

$$\frac{\mathrm{d}N}{\mathrm{d}z} = -\kappa N = -N\left(\frac{\rho_\mathrm{p} d_\mathrm{p}^2 V_\mathrm{b} C_\mathrm{c}}{4\mu R_\mathrm{b}^2} + \frac{g\rho_\mathrm{p} d_\mathrm{p}^2 C_\mathrm{c}}{24\mu R_\mathrm{b} V_\mathrm{b}} + 1.8\sqrt{\frac{k_\mathrm{B} T C_\mathrm{c}}{3\pi\mu d_\mathrm{p} V_\mathrm{b} R_\mathrm{b}^3}}\right). \quad (5)$$

The three terms appearing in the right-hand side of Eq. (5) represent inertial impaction, gravitational sedimentation, and Brownian diffusion, respectively. The Cunningham slip correction factor C_c is given as [16]:

$$C_\mathrm{c} = 1 + 2.284\frac{\lambda}{d_\mathrm{p}} + 1.116\frac{\lambda}{d_\mathrm{p}}\exp\left(-0.4995\frac{d_\mathrm{p}}{\lambda}\right), \quad (6)$$

where λ is the mean free path length of air molecules. For large enough Reynolds numbers, i.e., for $Re \geq 3.1(\rho_\mathrm{L}\sigma_\mathrm{s}^3/g\mu_\mathrm{L}^4)^{0.25}$, which holds true for the operational conditions considered in the present study, the rising velocity of a bubble is given as [17]:

$$V_\mathrm{b} = 1.53\left(\frac{g\sigma_\mathrm{s}}{\rho_\mathrm{L}}\right)^{0.25}. \quad (7)$$

Integrating Eq. (5), the particle collection efficiency of the swirl scrubber by pool scrubbing is

$$\eta_\mathrm{p} = 1 - \exp(-\kappa H_\mathrm{p}). \quad (8)$$

3.3. Wet scrubbing

Airborne particles that survived cyclone and pool scrubbing pass the wet scrubbing zone where they are removed by collisions with water droplets [18]. Particles smaller than 0.1 μm can be effectively collected as a result of their Brownian diffusion. Inertial impaction and interception may be important collection mechanisms for particles larger than 1 μm. The principles of Brownian diffusion and inertial impaction are similar to those in pool scrubbing. Collection by interception takes place when the streamline that a particle follows happens to come within the distance of the particle radius from the surface of a water drop.

During the wet scrubbing process, the change in particle concentration can be expressed by

$$\frac{\mathrm{d}N}{\mathrm{d}t} = -\frac{\pi}{4}D_\mathrm{d}^2 U_\mathrm{d}(E_\mathrm{dif} + E_\mathrm{int} + E_\mathrm{imp})N_\mathrm{d}N, \quad (9)$$

where t is time, D_d is the water drop diameter, and N_d is the concentration of water drops. The falling velocity of water drops can be parameterized as [19]:

$$U_\mathrm{d} = 130 D_\mathrm{d}^{1/2}, \quad (10)$$

where U_d and D_d are in SI units. The collision efficiencies due to Brownian diffusion, interception, and inertial impaction are given by Calvert [20] and Jung and Lee [21]:

$$E_\mathrm{dif} = 2\left(\frac{k_\mathrm{B} T C_\mathrm{c}}{4\sqrt{3}\mu d_\mathrm{p} D_\mathrm{d} U_\mathrm{d}}\right)^{2/3} \times \left[\frac{(1-\alpha)((3\mu_\mathrm{L}/\mu)+4)}{(1-(6/5)\alpha^{1/3}+(1/5)\alpha^2)+(\mu_\mathrm{L}/\mu)(1-(9/5)\alpha^{1/3}+\alpha+(1/5)\alpha^2)}\right]^{1/3}, \quad (11)$$

$$E_\mathrm{int} = \frac{1-\alpha}{(1-(6/5)\alpha^{1/3}+(1/5)\alpha^2)+(\mu_\mathrm{L}/\mu)(1-(9/5)\alpha^{1/3}+\alpha+(1/5)\alpha^2)} \times \left[\frac{d_\mathrm{p}/D_\mathrm{d}}{1+(d_\mathrm{p}/D_\mathrm{d})} + \frac{1}{2}\left(\frac{d_\mathrm{p}/D_\mathrm{d}}{1+(d_\mathrm{p}/D_\mathrm{d})}\right)^2\left(\frac{3\mu_\mathrm{L}}{\mu}+4\right)\right], \quad (12)$$

$$E_\mathrm{imp} = \left(\frac{\rho_\mathrm{p} d_\mathrm{p}^2 U_\mathrm{d}/18\mu D_\mathrm{d}}{(\rho_\mathrm{p} d_\mathrm{p}^2 U_\mathrm{d}/18\mu D_\mathrm{d}) + 0.35}\right)^2. \quad (13)$$

Integrating Eq. (9), the collection efficiency of the wet scrubbing process in the swirl scrubber is obtained:

$$\eta_\mathrm{w} = 1 - \exp\left[-\frac{\pi}{4}D_\mathrm{d}^2 U_\mathrm{d}(E_\mathrm{dif} + E_\mathrm{int} + E_\mathrm{imp})N_\mathrm{d} t_\mathrm{r}\right]. \quad (14)$$

4. Impact of operating conditions on collection efficiency

Among the parameters needed to calculate the collection efficiency of the swirl scrubber shown in the previous section, the scrubber dimensions, air stream flow rate, pool scrubbing layer thickness, water drop diameter, and water drop volume fraction are controlled by design and operational conditions. Smaller device size is preferable for higher performance of the cyclone, but limits the flow rate of the air stream that the device can treat. On the other hand, a larger device has higher wet scrubbing efficiency due to a longer residence time, but its size can cause other limitations in terms of installation space and operational cost. Design parameters, therefore, cannot be determined solely by the collection efficiency without practical considerations. Accordingly, in this section, we

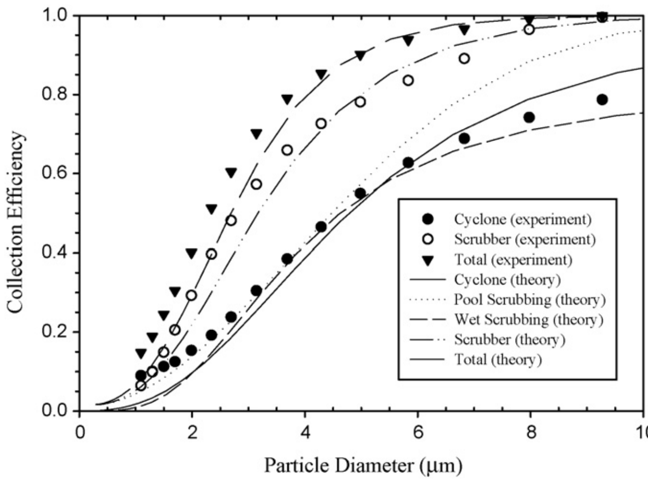

Fig. 4. Comparison of observed particle collection efficiency obtained with a swirl plate angle of 15°, a nozzle diameter of 7.5 mm, a water flow rate of 17.5 lpm, and a nozzle pressure of 0.7 kgf/cm^2 with the theoretical parameterization developed in Section 2.

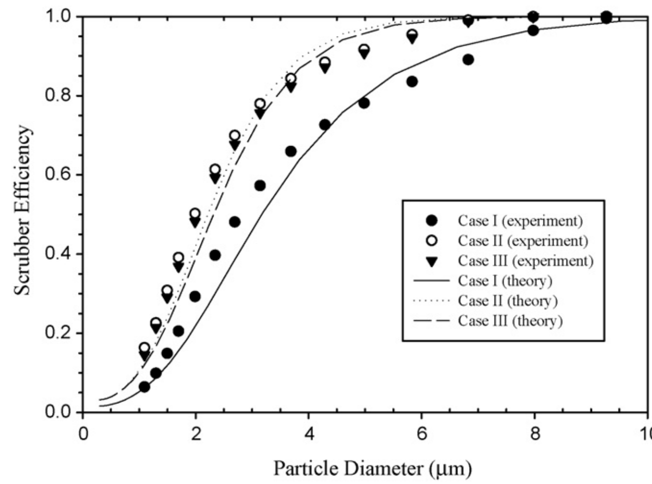

Fig. 5. Comparison of the collection efficiency due to scrubbing obtained under three different combinations of nozzle diameter and water flow rate with the theory. The experimental conditions and the parameter values that provide the best fit to experimental results are summarized in Table 1.

focus on the analyses of the impacts of operating conditions on collection efficiency. Based on the analyses, the experimental results reported in the sister paper [9] are discussed.

With increasing air flow rate, the amount of air treated per unit of time increases as does the cyclone efficiency, while the scrubbing efficiency decreases due to reduced residence time in the wet scrubbing zone. A thicker water layer can provide a higher collection efficiency by pool scrubbing at the cost of higher power consumption. The water layer thickness can be controlled by changing the swirl plate angle. According to our experiments [9], a swirl plate angle of 15° resulted in much higher collection efficiency with minimal increase in the pressure drop compared to swirl plate angles of 30° and 45°.

In order to obtain higher collection efficiency in wet scrubbing, smaller water drop diameters, i.e., more water drops for the same water flow rate, and larger water drop volume fractions are required. Smaller water drops are generated with higher nozzle pressure that induces stronger impingement of injected water on the impaction plate. Higher water drop volume fractions can be achieved simply by increasing water flow rate. Another way to increase the water drop volume fraction is to increase the nozzle pressure because smaller water drops generated under higher nozzle pressure have lower relaxation time and persist longer in air. In our experiments, we observed that the collection efficiency of the swirl scrubber increased with increasing nozzle pressure and water flow rate.

5. Analyses of experimental results

Fig. 4 compares the collection efficiencies obtained for a swirl plate angle of 15°, a nozzle diameter of 7.5 mm, a water flow rate of 17.5 lpm, and a nozzle pressure of 0.7 kgf/cm^2 with the theoretical parameterization developed in Section 3. 'Cyclone (experiment)' represents the experimentally obtained collection efficiencies without applying scrubbing medium. 'Total (experiment)' represents the experimentally obtained collection efficiencies with applying scrubbing medium. 'Scrubber (experiment)' represents the collection efficiencies calculated using the two above-mentioned efficiencies by the following equation:

$$\eta_s = \frac{\eta - \eta_c}{1 - \eta_c}. \tag{15}$$

'Cyclone (theory)', 'Pool Scrubbing (theory)', and 'Wet Scrubbing (theory)' mean the theoretically computed collection efficiencies for each collection mechanism, represented by Eqs. (3), (8) and (14), respectively. 'Scrubber (theory)' represents the theoretical collection efficiency by combined pool and wet scrubbings, calculated by

$$\eta_s = 1 - (1 - \eta_p)(1 - \eta_w). \tag{16}$$

'Total (theory)' represents the theoretical collection efficiency of the whole swirl scrubber, calculated by Eq. (1).

It is shown in Fig. 4 that the most important particle collection mechanism in the swirl scrubber is pool scrubbing. The experimentally obtained collection efficiencies were well modeled with D_d = 1 mm, α = 5E−4, R_b = 0.5 cm, and H_p = 10 cm. The collection efficiency due to scrubbing obtained under three different combinations of nozzle diameter, water flow rate, and nozzle pressure are compared with the theoretical parameterization in Fig. 5. The experimental conditions and the parameter values that provide the best fit to experimental results for those three cases are summarized in Table 1. It is noticed in Figs. 4 and 5 that the theoretical parameterization could model the particle collection efficiencies of each mechanism as well as of the whole swirl scrubber successfully. The error in terms of 50% cut-diameter was less than 10% for

Table 1
The experimental conditions for the three cases appearing in Fig. 5 and the parameter values that provide the best fit to experimental results

	Experimental condition			Theoretical parameters		
	Nozzle diameter (mm)	Water flow rate (lpm)	Nozzle pressure (kgf/cm^2)	D_d (mm)	$\alpha \times 10^3$	H_p (cm)
Case I	7.5	17.5	0.7	1	0.5	10
Case II	7.5	34	1.6	0.9	1.1	20
Case III	15	34	0.7	1	1	20

The angle of the swirl plate is 15° and R_b = 0.5 cm for all cases.

all the cases tested. Increasing water flow rate results in enhanced wet scrubbing and pool scrubbing collection efficiencies due to increased α and H_p, respectively (Case I vs. Case III). An increase in the nozzle pressure contributes to enhanced wet scrubbing collection efficiency as a result of decreased D_d (increased N_d) and increased α (Case II vs. Case III). It is shown in Figs. 4 and 5 and Table 1 that water flow rate plays a more critical role than nozzle pressure in determining the collection efficiency and that pool scrubbing contributes to particle collection more than wet scrubbing under the given range of operating conditions.

The theoretical parameter values used in Table 1 fall well within their feasible ranges in practical applications of wet and pool scrubbers, which demonstrates that the theoretical parameterization developed in this study is appropriate for explaining the collection efficiency of our novel swirl scrubber. The selection of H_p values is based on experimental observation in this study. The bubble radius values of between 0.1 and 1.5 cm have been repeatedly reported in the literature on pool scrubbing. In a series of pool scrubbing experiments in which movies were taken with a camera and were analyzed to determine the bubble sizes and velocities, a bubble radius of about 0.3 cm was found, independent of the air flow rate [22,23]. A bubble radius of 0.3 cm was also reported by Cartellier [24]. In a pool scrubbing experiment using a porous plug, Anagbo and Brimacombe [25] reported bubble diameter between 0.4 and 3 cm depending upon the degree of coalescence among the bubbles. Akbar and Ghiaasiaan [26] conducted a numerical simulation study on removal of aerosol particles in a pool scrubbing system using a hybrid Eulerian–Monte Carlo method. In their simulations, the bubble diameters between 0.3 and 0.5 cm were used, which represented the experiments of Herranz et al. [27]. The best-fit value 0.5 cm of this study is larger than the values reported in the literature for coalescence-free conditions by a factor of about 2 on average, which indicates that coalescence among the bubbles might have taken place in this study due to high gas flow rate.

Selections of the water drop size and the liquid volume fraction were less straightforward because the method of water drop generation used in this study is different from conventional methods. The best-fit water drop diameter of 0.9–1 mm is more or less larger than the typical drop sizes in conventional wet scrubbers using pneumatic two-fluid atomization procedure, which range several tens to several hundreds μm [28]. In this study, the water drops were created by impingement of water on the impaction plate, which seemingly led to larger drop size than the conventional atomization methods. This larger drop size seems to have affected the liquid volume fraction. The best-fit liquid volume fraction values, ranging from 0.0005 to 0.0011, are less than the corresponding liquid-to-gas ratio which ranged from 0.001 to 0.002 by a factor of about 2. This is reasonable because considerable fraction of water drops reach the scrubber wall, due to relatively large inertia, and are removed from the wet scrubbing volume before they have enough time to collect particles.

6. Discussion on possible variations

In our experiments, rod impaction plates were designed as shown in Fig. 6, installed, and tested to further reduce water drop size while all other conditions were left unchanged. Fig. 7 shows the results together with the best-fit theoretical parameterization curves. In this figure, the legend "without rod" represents Case II shown in Table 1, while "with rod" refers to the new test case with addition of the rod impaction plate. The best fit was obtained with D_d = 0.5 mm and α = 1.5E−3 for the new case. Comparing these values with those for Case II in Table 1 (D_d = 0.9 mm and α = 1.1E−3), the effect of the rod impaction plate can be deduced, i.e., a decrease in water drop size and an increase in water drop volume fraction.

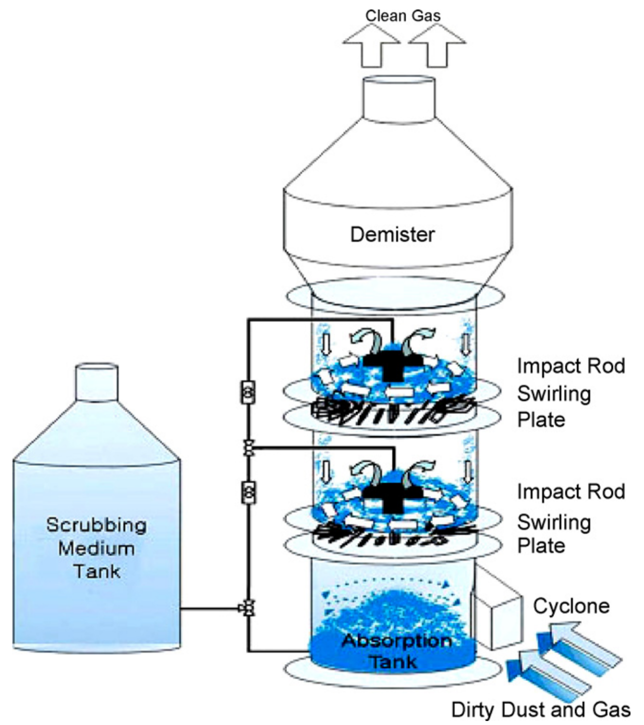

Fig. 6. A schematic of the novel double-staged swirl cyclone scrubber with impaction rods.

Multiple stages of the swirl plate and the nozzle-impaction plate (rod) system can be installed in series to increase the collection efficiency of the swirl scrubber (Fig. 6). Fig. 8 represents the theoretically parameterized collection efficiency of the double-stage swirl scrubber as shown in Fig. 6. It is shown in this figure that the collection efficiency for every particle size is improved for the double-stage swirl scrubber compared to the single-stage one. In particular, the collection efficiency of ultrafine particles (or nanoparticles) less then 100 nm increases significantly owing to enhanced pool and wet scrubbing efficiencies by Brownian diffusion. The collection efficiency of particles in the 0.1–1 μm

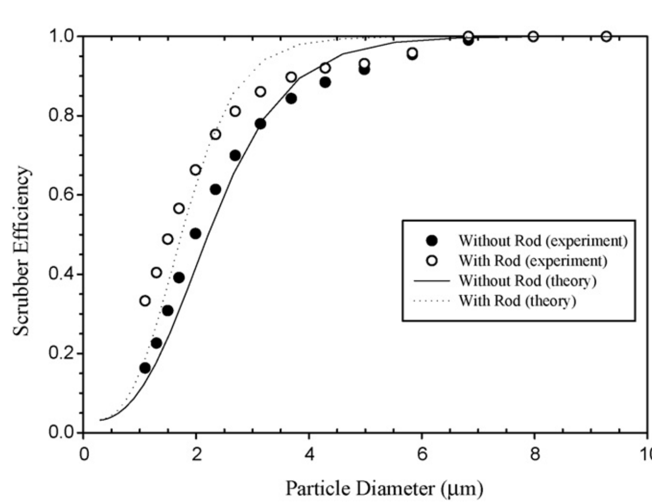

Fig. 7. The effect of the installation of a rod impaction plate.

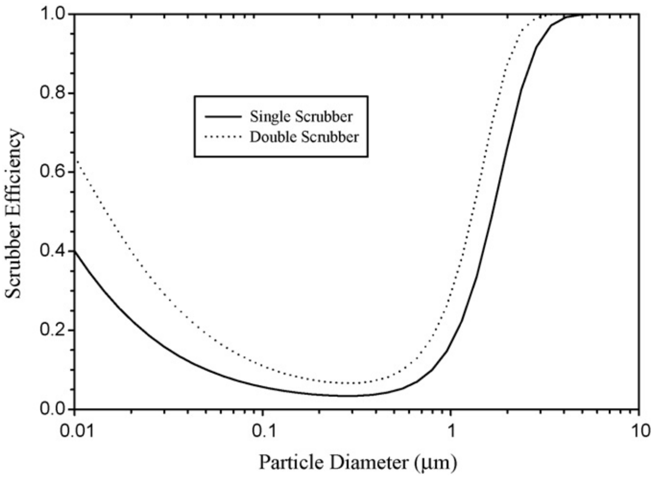

Fig. 8. Theoretically parameterized collection efficiency of the double-stage swirl scrubber.

size range, however, still remains very low, and this should be addressed in a future study to further improve the device's performance.

7. Conclusions

Theoretical analyses have been carried out for the swirl scrubber. The particle collection efficiencies obtained from experiments under various design and operating parameters were explained theoretically to provide guidelines for optimal design and operation of the device. Under the assumption that cyclone filtering, pool scrubbing, and wet scrubbing take place independently in series, a theoretical parameterization has been developed. The suggested parameterization adequately explained the observed dependency of particle collection efficiency on operating parameters.

An increase in the water flow rate results in enhanced wet scrubbing and pool scrubbing collection efficiencies due to increased water drop volume fraction and increased pool scrubbing layer thickness. An increase in the nozzle pressure leads to an increased number of water drops and increased water drop volume fraction resulting in enhanced wet scrubbing collection efficiency. Water flow rate plays a more critical role than nozzle pressure in determining the collection efficiency, and pool scrubbing contributes to the particle collection more than wet scrubbing under the operational conditions considered. The theoretical parameter values which give the best fit to the observations fall in their feasible ranges in practical applications, demonstrating that the theoretical parameterization developed in this study is appropriate for explaining the experimental results.

The enhanced particle collection obtained with the addition of a rod impaction plate can be explained as a result of the decrease in water drop size and the increase in water drop volume fraction. A double-stage swirl scrubber can be designed to attain improved particle collection efficiency, particularly for ultrafine particles. The low collection efficiency of particles in the 0.1–1 μm size range should be addressed in a future study to further improve the device's performance.

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