Available online at www.sciencedirect.com

ScienceDirect

Aerosol Science 39 (2008) 1079–1088

Journal of
Aerosol Science

www.elsevier.com/locate/jaerosci

Development and application of a novel swirl cyclone scrubber—(1) Experimental

Byeong-Kyu Lee[a,*], Kwang-Ryun Jung[a], Sung-Hoon Park[b]

[a]*Department of Civil and Environmental Engineering, University of Ulsan, Ulsan 680-749, Republic of Korea*
[b]*Department of Environmental Engineering, Sunchon National University, Suncheon, Jeonnam 540-742, Republic of Korea*

Received 30 November 2007; received in revised form 22 April 2008; accepted 22 July 2008

Abstract

Conventional cyclones have a lower collection efficiency for smaller particles and conventional wet scrubbers have significant clogging and fouling problems by salt formation at the tip, the inside and outside of the nozzles, the tubes and the walls of scrubbers. Also, many companies and manufacturing sites have been in trouble for collecting their adhesive particulates. The novel swirl scrubber that we have developed consists mainly of a cyclone and a swirl scrubber with an impact cone and plates. This study reports the collection efficiency of particulates and the application of the novel swirl scrubber. The particle collection efficiency as a function of particle size was investigated with changes of plate angles, nozzle size and pressure, and volumetric flow rate of scrubbing medium. The particle collection efficiency increased with a decrease in plate angle, an increase in pressure of scrubbing medium at the nozzle tip, and an increase in volumetric flow rate of the scrubbing medium. The collection efficiency of PM_{10} by scrubbing effect was much higher than that by cyclonic effect. In particular, the total increase in particle collection efficiency by scrubbing effect was significant (around 2.5 μm) in particle aerodynamic diameter. The developed novel swirl scrubber can be used for significantly increasing the collection efficiency of TSP, PM_{10}, and $PM_{2.5}$, in particular, which have adhesive characteristics. The costs for installation, operation and maintenance of the scrubber system are much cheaper than those of cyclones and scrubbers or other particulate collecting devices.

Keywords: Swirl; Scrubbing; Cyclone; Plate; Sticky particles

1. Introduction

Cyclones have been very useful as pre-cleaning devices of particles which are larger than 10 μm in their aerodynamic diameter. However, it is not easy to get a higher collection efficiency than 90% with conventional cyclones if the particle size is not larger than 25 μm. Even though advanced high-efficiency cyclones could get a collection efficiency of approximately 70% down to 5 μm particles, the efficiency rapidly decreases with a size decrease in particles (Wark, Warner, & Davis, 1998; Yoshida, Ono, & Fukui, 2005). The significant pressure loss and operation cost increase accompanied by improving collection efficiency of particles are also other drawbacks of cyclones.

Wet scrubbers have been popularly used for the collection of acidic gases, mists, and particles with significantly reducing risks of fire, explosion and erosion (Chien & Chu, 2000; Deshwal et al., 2008; Jin, Deshwal, Park, & Lee, 2006;

---

[*] Corresponding author. Tel.: +82 52 259 2864; fax: +82 52 259 2629.
E-mail address: bklee@ulsan.ac.kr (B.-K. Lee).

doi:10.1016/j.jaerosci.2008.07.010

Li & Cai, 2006). Since wet scrubbers use mostly water for the scrubbing of particulate matter (Park, Jung, Jung, Lee, & Lee, 2005), it is very common to have water pollution problems by insufficient treatment, visible plume problems at stacks and freezing problems of scrubbing medium under cold weather situations during winter. Conventional wet scrubbers also have significant clogging and fouling problems by salt formation at the tip, the inside and outside of the nozzles, the tubes and the walls of scrubbers. Other disadvantages of conventional wet scrubbing systems are the expensive costs for treatment or disposal of sludge and high operation cost incurred as a result of the improvement of control efficiency (Kim, Jung, Oh, & Lee, 2001; Meikap & Biswas, 2004).

Many companies and manufacturing sites have been in trouble for collecting their adhesive particulates, such as tars and mists with high temperature. Increased costs for control of particulate matter and sludge have also been a heavy burden for many companies. Therefore, it is necessary to develop a cheap and effective control device of particulate matters that have acidic and sticky properties.

There have been many reports on improving the performance or application of wet scrubbers and/or cyclones (Chang, Chi, & Chang-Chien, 2004; Dwari, Biswas, & Meikap, 2004; Gemci & Ebert, 1992; Laitinen, Hautanen, & Keskinen, 1997; Li & Cai, 2004, 2006; Meikap, Kundu, & Biswas, 2002; Pei, 1996; Schwarz, Smolík, Veselý, Sýkorová, & Kučera, 1996; Xu, Guo, Kaneko, & Kato, 2000; Yang, Jung, Wang, & Hsieh, 2005; Yang & Yoshida, 2004; Yoshida, Yoshikawa, Fukui, & Yamamoto, 2008). A swirl promoter scrubber to improve the aerosol deposition in a venturi scrubber has been developed by Mayinger and Lehner (1995). There are a few available studies to deal with sticky particles (Hasler & Nussbaumer, 1999; Li & Cai, 2006; Li, Rudolph, & Peukert, 2006; Maury, Murphy, Kumar, Shi, & Lee, 2005; Müller, Peukert, Polke, & Stenger, 2004; Peukert & Wadenpohl, 2001).

We have developed a novel swirl scrubber that mainly consists of a cyclone and a swirl scrubber with a rod impact plate and swirl plates to overcome the many drawbacks of conventional cyclones and wet scrubbers (Yang & Yoshida, 2004). This paper reports on the development, the collection efficiency analysis of particulate matter and the application of the novel swirl scrubber systems. Theoretical analyses for the swirl scrubber systems are presented in the sister paper of this paper (Park & Lee, 2008).

2. Novel swirl cyclone scrubber system

Fig. 1 shows a schematic of a system analyzing collection efficiency of particles using the novel swirl cyclone scrubber (NSCS) that we have developed. The NSCS system consists of mainly a cyclone, swirl plates, a scrubber, feeding and circulation devices of scrubbing medium, and demister. After gas stream including particulate matter passes through the cyclone zone, it enters the swirl plate zones and then experiences the wet scrubber zone.

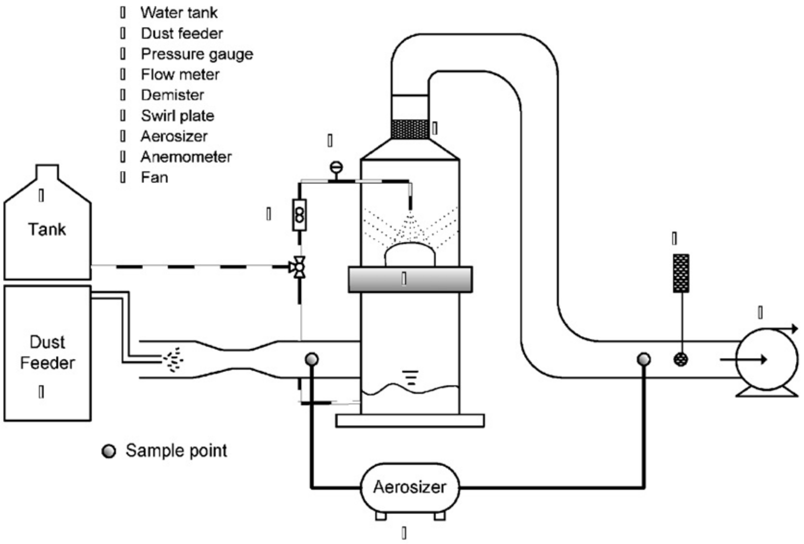

Fig. 1. A schematic of the system analyzing collection efficiency of particles using the novel swirl cyclone scrubber (NSCS).

Gas and particles would have more than six times as many chances to contact collection devices or the scrubbing medium in the NSCS system. First, the gas stream containing particles enters the cyclone with tangential direction through the vane attached in the bottom part of the NSCS. The gas stream will come in contact with the cyclone wall by centrifugal forces and most of the large particles which are larger than 10 μm in their aerodynamic diameter will be collected in the cyclone zone. Second, the scrubbing medium (water) passes through the swirl plate and flows down resulting in a water coating on the cyclone wall. The water coating improves the collection efficiency of particles and gases inside the cyclone. Third, the gas stream passing the swirl plate zone comes in contact with the swirl plates by inertial impaction, direct interception, and Brownian diffusion. Fourth, 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 zone meet the water layer. 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 NSCS 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. Fifth, the scrubbing medium also flows down the scrubber body and produces a water coating on the wall of the scrubber. The gases and particles that have passed through the swirl plate zone and the swirling water layer circulate in the scrubber body zone. The circulating gases and particles are sent upward and come in contact with the water coating of the scrubber body. Sixth, the gases and particles 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 would 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. Seventh, fog and/or mist zone exists in the upper part of the scrubber zone that also contributes to an additional collection of the gases and particles. Eighth, the gases and particles, which were not collected yet in the cyclone, swirl plate, and scrubber zones, pass through the demister zone located above the scrubber zone for final collection in the NSCS system.

3. Methods

This study analyzed changes in the collection efficiency of particles using a dust feeder, a fan, a pump, an aerosol measurement system and the NSCS system (Fig. 1). Particle collection efficiencies were computed by the difference between particle number concentrations measured at the inlet and at the outlet using the aerosol measurement system (Aerosizer, Model Mach II and LD, API).

The dust feeder (Micro Feeder, Model IMF-2, SIBATA Scientific Technology Ltd.) generates fly ash particles ranging from 0.1 to larger than 10.0 μm in aerodynamic diameter. The produced particles are sent into the NSCS system with a feed velocity of 8.9 m/s, i.e., with a volumetric flow rate of 16.8 m^3/min, by the fan located at the end of the analyzing system.

The air stream containing particles are first passed through the inlet of the NSCS into the cyclone zone. Large particles are collected on the wall surface of the cyclone by centrifugal force. Then the stream proceeds though the swirl plates located between the cyclone and the scrubber zones. Next, they are circulated in the scrubber and passed through the upper part of the scrubber system. The scrubbing medium (e.g., water) is introduced into the scrubber system through a nozzle connected by a water tank driven by a pump. Water is injected on an impaction plate (round rod) producing water spray in the scrubber system. The water spray drops fall by gravity or collide on the scrubber wall and flow down on the swirl plates to form a swirling water layer with a depth ranging from 5 to 20 cm. Particles were scrubbed by contact, due to inertial impaction or direct interception, with the water drops dispersed in the scrubber zone. Also, particles make contact with the mist or fog generated from the scrubbing medium in the upper part of the scrubber zone and they are removed by passing through a demister.

To determine the average collection efficiency, seven repeated measurements were conducted for a given experimental set. Finally, the remaining particle fractions that were not removed in the NSCS system were monitored at the outlet. This study analyzed collection efficiencies of the test particles as a function of swirl plate angle (15°, 30°, 45°), supply pressure (0.7, 1.6, 2.0, 3.0, 4.0 kgf/cm^2), volumetric flow rate of scrubbing medium (7.5–8.0, 17.5, 30.0, 34.0 L/min), which correspond to liquid-to-gas ratio of 0.447–2.03 L/m^3, generation amount and size of the generated particles, and nozzle size (Φ 2.0, 7.5, 9.0, 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, this study identified the particle collection efficiency by the cyclone, by the scrubber, and by the whole NSCS systems.

The system was operated first without water feeding to measure the particle collection efficiency of the cyclone (E_{cyc}) only and then with water feeding for the efficiency of the whole NSCS system (E_{NSCS}). The collection efficiency of wet scrubbing (E_{scr}) was then calculated by $1-E_{\text{scr}}=(1-E_{\text{NSCS}})/(1-E_{\text{cyc}})$.

4. Results and discussion

4.1. Effect of nozzle pressure

Fig. 2 shows the collection efficiency, based on particle number, of particles as a function of water pressure in nozzle (ϕ: 2 mm) feeding scrubbing medium to the scrubber in the NSCS (early development stage) maintaining a constant swirl plate angle of 45°. Even though the total efficiencies represent the combined collection effects of particles by the simple cyclone and scrubber included in the NSCS system, they were not that successful. That is because the particles in the NSCS at that stage did not get sufficiently effective revolution in the cyclone section and good contact with water spray in the scrubber section in spite of the nozzle pressure change. However, the increase effect in collection efficiency of particles with an increase in nozzle pressure was identified in the optimized NSCS system. This is discussed further in Section 4.3.

4.2. Effect of swirl plate angle

Fig. 3 shows the collection efficiency of particles measured based on particle number as a function of swirl plate angle in the scrubber section of the NSCS with middle development stage. As the swirl plate angle decreased and the size of particles increased, the general collection efficiency of particles significantly increased. When the angle changed from 45° to 30°, in particular, the improvement in collection efficiency by the scrubber was much higher than that by cyclone. In particular, the improvement in the coarse particle zone was higher than that in the fine particle zone. Also, the further reduction in angle of the swirl plate (from 30° to 15°) showed a much higher increase in particle collection efficiency, in particular, even in the fine particle zone. This is also discussed further in Section 4.3.

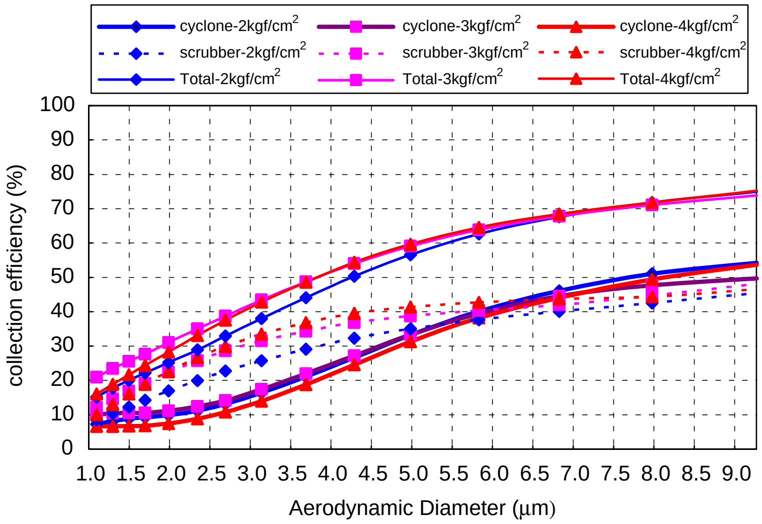

Fig. 2. Collection efficiency of particles as a function of nozzle pressure of scrubber in the NSCS with early development stage.

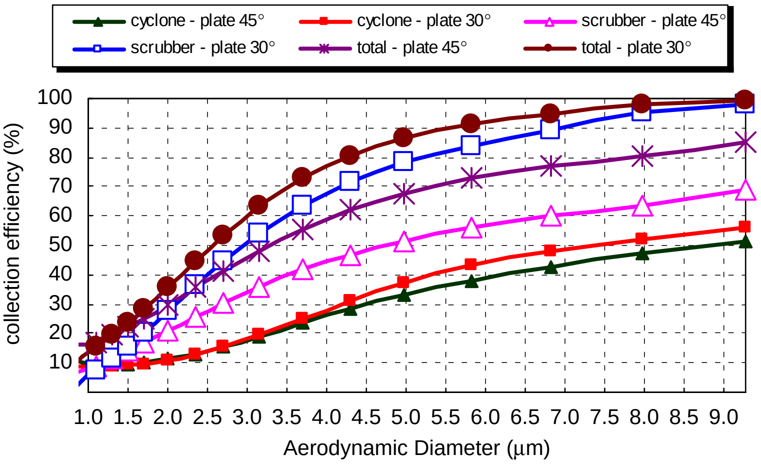

Fig. 3. Collection efficiency of particles as a function of swirl plate angle of the NSCS with middle development stage.

4.3. Swirl effect of scrubbing medium

An almost optimized NSCS system has been developed based on the previous experiments. In the almost optimized NSCS system, the feed rate of the scrubbing medium significantly increased as compared to the previous stage NSCS systems and thus the swirling and circulation of the scrubbing medium was observed on the swirl plate with water depth depending on feed rate and swirl plate angle. Figs. 4a–c show the overall collection efficiency (the combined collection effects by cyclone, scrubber, and swirl plate) of particles as a function of swirl plate angle and volume of the NSCS system at optimized stage. These figures represent the overall collection efficiency of particles using three experimental sets (nozzle ϕ of 15 mm and the feed rate (or swirl volumetric rate) of scrubbing medium of 34 L/min, nozzle ϕ of 7.5 mm and the feed rate of scrubbing medium of 34 L/min, nozzle ϕ of 7.5 mm and the feed rate of scrubbing medium of 17.5 L/min). In general, the overall collection efficiency of particles significantly increased with a decrease in the swirl plate angle, an increase in the swirl volumetric rate (feed rate) of scrubbing medium, and a decrease in the nozzle size (diameter). The overall best collection efficiency was identified with plate angle of 15°, supply pressure of scrubbing medium of 1.6 kgf/cm^2, nozzle diameter of 7.5 mm, and volumetric flow of 34 L/min. The NSCS system with swirl plate angle of 45° did not show the swirling of scrubbing medium. Thus, the collection of particles, such as inertial impaction or direct interception, by the circulation of the swirling medium would be significantly lower than that in the NSCS system with a swirl plate angle of 15°, which has a significant amount of swirling. In the swirl plate angle of 45°, however, the collection efficiency of the fine fraction of particles relatively increased with a decrease in nozzle size. In the swirl plate angle of 30°, which has a little swirling effect, the collection efficiency of the fine fraction of particles highly increased with an increase in nozzle size and feed rate of scrubbing medium. Also, the overall collection efficiency of coarse fraction of particles in the 30° system significantly increased, due to swirling and circulation effects of the medium, as compared to that in the 45° system. The swirl plate angle of 15° showed a significant amount of swirling and circulation effects of the scrubbing medium and thus resulted in the significantly increased overall collection efficiency as compared to that of 30° or 45°. In a comparison of the same amount of swirling medium, 34 L/min, the overall collection efficiency of the NSCS system with nozzle ϕ of 7.5 mm was higher than that with nozzle ϕ of 15 mm. The smaller the nozzle, the higher nozzle pressure was observed resulting in smaller droplets. Therefore, the NSCS system with a smaller nozzle of the same swirling and circulation of the scrubbing medium would have more effective contact with scrubbing medium than that with a larger nozzle.

4.4. Stability of overall collection efficiency

Concentrations of particles loaded into a particle control device could have some variation resulting in instability of the overall collection efficiency of particles. This study evaluated the stability in overall collection efficiency of particles with a change of generation concentration of particles at the inlet of the NSCS system. Table 1 presents a

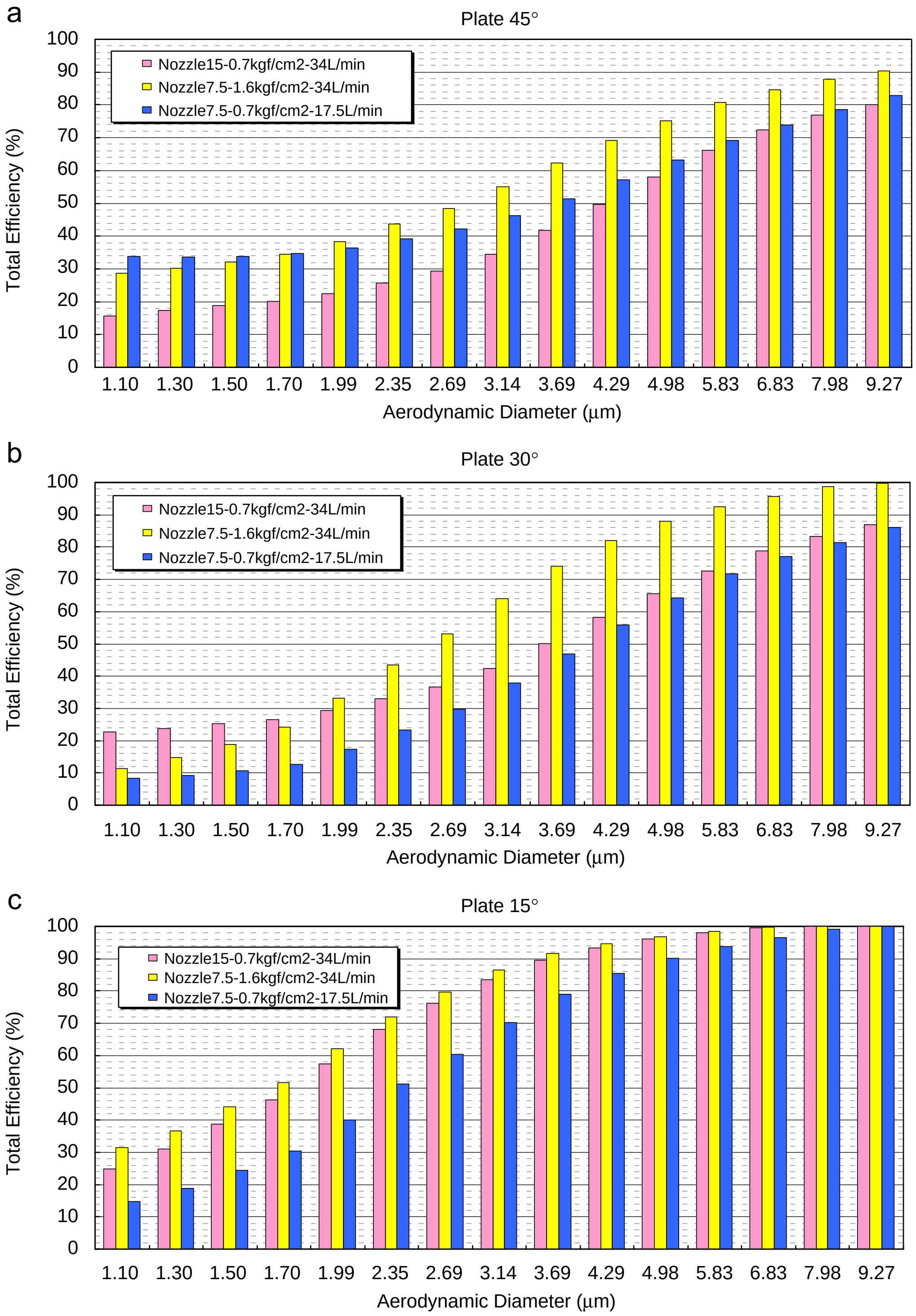

Fig. 4. Collection efficiency of particles as a function of swirl plate angle and volume of the NSCS: (a) swirl plate angle of 45°, (b) swirl plate angle of 30° and (c) swirl plate angle of 15°.

Table 1
Stability of overall mass collection efficiency as a function of particle loading in the NSCS.

Target generation concentration (mg/m^3)	Generated mass concentration (mg/m^3)	Overall mass collection efficiency (%)
100	93.21 ± 6.45	97.22 ± 0.44
75	74.67 ± 0.93	97.64 ± 0.17
50	50.95 ± 3.81	97.24 ± 0.34
30	31.93 ± 0.89	97.03 ± 0.24

Repeated measurement, $n = 5$.

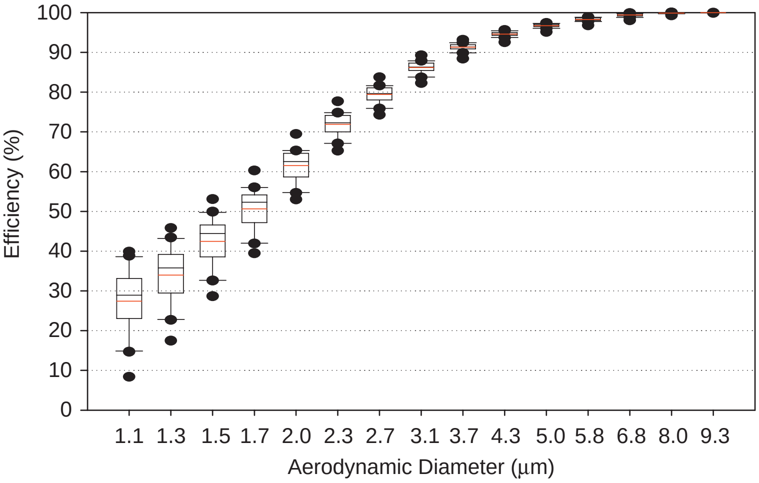

Fig. 5. Collection efficiency of particles as a function of particle size in the NSCS.

variation of dust loading or generation concentration of particles in the test inlet of the NSCS system and also the stability of the overall collection efficiency of particles by the NSCS system (nozzle ϕ of 15 mm, feed of scrubbing medium of 34 L/min, and 1.6 kgf/cm^2). Even though there was a variation of mass concentration generated in the test design, the NSCS system showed a very stable overall collection efficiency of particles in a range of dust loading from 30 to 100 mg/m^3.

Fig. 5 shows the overall particle collection efficiency of the NSCS system as a function of particle size. The collection efficiency substantially increased with an increase in particle size. The variation in particle collection efficiency decreased with an increase in particle size and there was almost no variation of particles which are above 5.0 µm in diameter. The variation might be due to the difference in generation amount or pattern of the tested particles. The high variation in a smaller particle size also means that it is relatively difficult to generate constantly the test particles having diameters around or less than 1.0 µm. For 2.5 and 5 µm particles, a high-throughput cyclone, a typical high-efficiency cyclone, and a typical venturi scrubber have a collection efficiency of about 20% and 35%, 60% and 75%, and 95% and 99%, respectively (Wark et al., 1998). An optimized NSCS system identified a collection efficiency of above 86% and 97% for 2.5 and 5 µm particles, respectively.

4.5. System optimization

A round-shaped rod impaction plate was added in the place between the tip of the nozzle and the swirl plate zone to optimize the NSCS system. The scrubbing medium provided through the nozzle was impacted producing a more fine size of water spray or droplet. Fig. 6 shows collection efficiencies of particles categorizing collection effects by cyclone and scrubber zones in an optimized NSCS system with a rod impaction plate. Fig. 7 compares the overall collection efficiency of particles among the NSCS systems (efficiency of the NSCS systems as a function of swirl plate angle without the rod impaction plate and that of an optimized NSCS system with the rod impaction plate and swirl plate

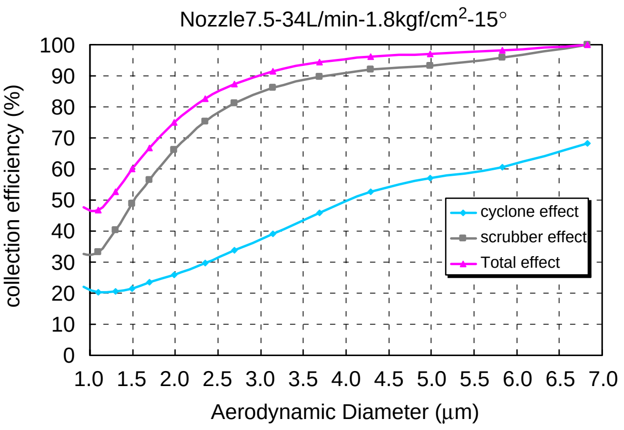

Fig. 6. Collection efficiency of particles by an optimized NSCS system.

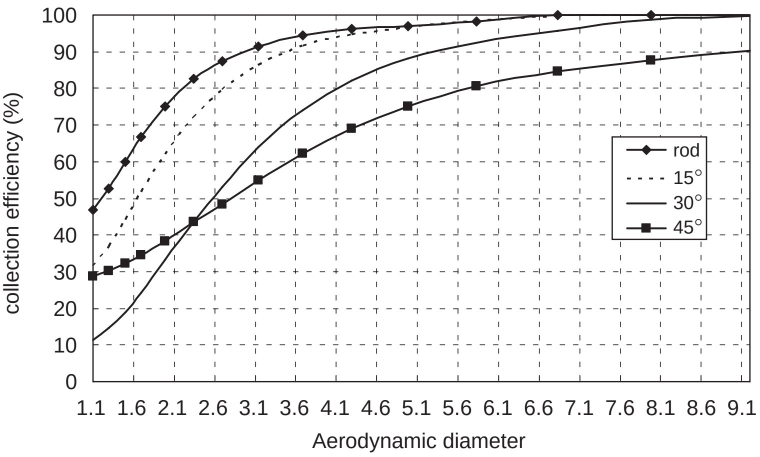

Fig. 7. A comparison of collection efficiency of particles among the NSCS systems.

angle of 15°). The optimized NSCS system with rod impaction plate and swirl plate angle of 15° showed substantially improved collection efficiency, in particular, of particles less than 2.5 μm in an aerodynamic diameter. The collection efficiency by the cyclone zone in the optimized NSCS system was similar to that of conventional or high-throughput cyclone. Placement of the rod impaction plate near the tip of the nozzle in the NSCS system resulted in a slight increase from 1.6 to 1.8 kgf/m^2. Thus this improved efficiency of particles of less than 2.5 μm might be due to a more effective spray or size decrease of sprayed water droplets by the addition of the rod impaction plate.

4.6. Pressure drop and application

Even venturi scrubbers have high particle collection efficiencies, but they usually have significant pressure drop ranging from 300 to 900 mmH$_2$O. However, the developed NSCS system can almost neglect the pressure drop ranging from 110 to 120 mmH$_2$O for the case of the highest particle collection efficiency (swirl plate angle of 15° and the water volumetric flow rate of 34 L/min). Furthermore, the NSCS system has many unique advantages over conventional particulate removal systems that make the application of the system in a number of circumstances promising. Most of particle collection devices have had a difficulty in dealing with sticky particulates and clogging problems by salt formation inside the collection device (Hasler & Nussbaumer, 1999; Li & Cai, 2006; Maury et al., 2005; Peukert & Wadenpohl, 2001). The NSCS system has completely solved these problems. Also, the total building cost of the

NSCS system is about 25–40% of a wet electrostatic precipitator that has a very popular industrial application. The NSCS system consists of simple parts and the system operation is very simple. The water used as scrubbing medium is recyclable. Thus, the operation and maintenance costs of the NSCS system are also very cheap. In summary, the NSCS system has a high and stable particle collection efficiency, low pressure drop, and low building and operational costs. Therefore, the NSCS system could be a very useful device for particle control in many industrial scale applications.

5. Conclusions

The novel swirl scrubber developed to overcome many problems that conventional cyclones and wet scrubbers have could lead to a significant increase in collection efficiency of, especially adhesive, TSP, PM_{10}, and $PM_{2.5}$. The particle collection efficiency increased with a decrease in the plate angle, an increase in the pressure of scrubbing medium at the nozzle tip, and an increase in the volumetric flow rate of the scrubbing medium. The best overall mass collection efficiency of particles was obtained by the NSCS system with a swirl plate angle of 15°, a nozzle ϕ of 7.5 mm (1.6 kgf/cm^2), and the feed rate of scrubbing medium of 34 L/min among the tested NSCS systems. The optimized NSCS system with the addition of round-shaped rod impaction plate in the place between the nozzle tip and the swirl plate zone showed an additional improvement of the overall collection efficiency, in particular, of particles less than 2.5 µm in aerodynamic diameter. The optimized NSCS system has 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 NSCS system could be a very useful device for particle control in many industrial scale applications.

Acknowledgments

This study was funded by ECO-TSC through the Industrial Corporation of the University of Ulsan, Ulsan, Korea. The authors wish to acknowledge the excellent assistance provided by Ju-Hyuck Lee and Jung-Gi Kim who generously helped them conduct the performance tests of the NSCS system.

References

Chang, M. B., Chi, K. H., & Chang-Chien, G. P. (2004). Evaluation of PCDD/F congener distributions in MWI flue gas treated with SCR catalysts. *Chemosphere*, *55*, 1457–1467.

Chien, T. W., & Chu, H. (2000). Removal of SO_2 and NO from flue gas by wet scrubbing using an aqueous $NaClO_2$ solution. *Journal of Hazardous Materials*, *80*, 43–57.

Deshwal, B. R., Jin, D. S., Lee, S. H., Moon, S. H., Jung, J. H., & Lee, H. K. (2008). Removal of NO from flue gas by aqueous chlorine-dioxide scrubbing solution in a lab-scale bubbling reactor. *Journal of Hazardous Materials*, *150*, 649–655.

Dwari, R. K., Biswas, M. N., & Meikap, B. C. (2004). Performance characteristics for particles of sand FCC and fly ash in a novel hydrocyclone. *Chemical Engineering Science*, *59*, 671–684.

Gemci, T., & Ebert, F. (1992). Prediction of the particle capture efficiency based on the combined mechanisms (turbulent diffusion, inertial impaction, interception, and gravitation) by a 3-D simulation of a wet scrubber. *Journal of Aerosol Science*, *23*, 769–772.

Hasler, P., & Nussbaumer, T. (1999). Gas cleaning for IC engine applications from fixed bed biomass gasification. *Biomass and Bioenergy*, *16*, 385–395.

Jin, D.-S., Deshwal, B.-R., Park, Y.-S., & Lee, H.-K. (2006). Simultaneous removal of SO_2 and NO by wet scrubbing using aqueous chlorine dioxide solution. *Journal of Hazardous Materials*, *135*, 412–417.

Kim, H. T., Jung, C. H., Oh, S. N., & Lee, K. W. (2001). Particle removal efficiency of gravitational wet scrubber considering diffusion, interception, and impaction. *Environmental Engineering Science*, *18*, 125–136.

Laitinen, A., Hautanen, J., & Keskinen, J. (1997). Effect of the space charge precipitation on wet scrubber fine particle removal efficiency. *Journal of Aerosol Science*, *28*, S287–S288.

Li, J., & Cai, W. (2004). Study of the cut diameter of solid–gas separation in cyclone with electrostatic excitation. *Journal of Electrostatics*, *60*, 15–23.

Li, J., & Cai, W. (2006). Theory and application of cyclone with impulse electrostatic excitation for cleaning molecular gas. *Journal of Electrostatics*, *64*, 254–258.

Li, Q., Rudolph, V., & Peukert, W. (2006). London–van der Waals adhesiveness of rough particles. *Powder Technology*, *161*, 248–255.

Maury, M., Murphy, K., Kumar, S., Shi, L., & Lee, G. (2005). Effects of process variables on the powder yield of spray-dried trehalose on a laboratory spray-dryer. *European Journal of Pharmaceutics and Biopharmaceutics*, *59*, 565–573.

Mayinger, F., & Lehner, M. (1995). Operating results and aerosol deposition of a venturi scrubber in self-priming operation. *Chemical Engineering and Processing*, *34*, 283–288.

Meikap, B. C., & Biswas, M. N. (2004). Fly-ash removal efficiency in a modified multi-stage bubble column scrubber. *Separation and Purification Technology*, *36*, 177–190.

Meikap, B. C., Kundu, G., & Biswas, M. N. (2002). Modeling of a novel multi-stage bubble column scrubber for flue gas desulfurization. *Chemical Engineering Journal*, *86*, 331–342.

Müller, F., Peukert, W., Polke, R., & Stenger, F. (2004). Dispersing nanoparticles in liquids. *International Journal of Mineral Processing*, *74*(Suppl. 1), S31–S41.

Park, S. H., Jung, C. H., Jung, K. R., Lee, B. K., & Lee, K. W. (2005). Wet scrubbing of polydisperse aerosols by freely falling droplets. *Journal of Aerosol Science*, *36*, 1444–1458.

Park, S. H., & Lee, B. K. (2008). Development and application of a novel swirl cyclone scrubber—(2) theoretical. *Journal of Hazardous Materials*, doi:10.1016/j.jhazmat.2008.08.023.

Pei, Q. (1996). New technology of wet scrubbing and desulfurization for middle and small coal-fired boiler flue gas and analysis of its process economy. *Fuel and Energy Abstracts*, *37*, 225.

Peukert, W., & Wadenpohl, C. (2001). Industrial separation of fine particles with difficult dust properties. *Powder Technology*, *118*, 136–148.

Schwarz, J., Smolík, J., Veselý, V., Sýkorová, I., & Kučera, J. (1996). Particulate emissions from the fludised bed combustion of brown coal. *Journal of Aerosol Science*, *27*, S359–S360.

Wark, K., Warner, G. F., & Davis, W. T. (1998). Particulate control. In *Air pollution: Its origin and control* (3rd ed., 278pp). Addison-Wesley.

Xu, G., Guo, Q., Kaneko, T., & Kato, K. (2000). A new semi-dry desulfurization process using a powder-particle spouted bed. *Advances in Environmental Research*, *4*, 9–18.

Yang, H.-H., Jung, R.-C., Wang, Y.-F., & Hsieh, L.-T. (2005). Polycyclic aromatic hydrocarbon emissions from joss paper furnaces. *Atmospheric Environment*, *39*, 3305–3312.

Yang, K.-S., & Yoshida, H. (2004). Effect of mist injection position on particle separation performance of cyclone scrubber. *Separation Purification Technology*, *37*, 221–230.

Yoshida, H., Ono, K., & Fukui, K. (2005). The effect of a new method of fluid flow control on submicron particle classification in gas-cyclones. *Powder Technology*, *149*, 139–147.

Yoshida, H., Yoshikawa, S., Fukui, S., & Yamamoto, T. (2008). Effect of multi-inlet flow on particle classification performance of hydro-cyclones. *Powder Technology*, *184*, 352–360.