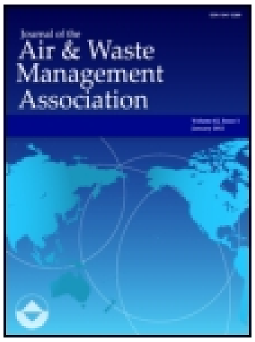


Journal of the Air & Waste Management Association

ISSN: 1096-2247 (Print) 2162-2906 (Online) Journal homepage: https://www.tandfonline.com/loi/uawm20

Evaluating the performance of a turbulent wet scrubber for scrubbing particulate matter

Byeong-Kyu Lee , B. Raj Mohan , Seung-Hyeok Byeon , Kyung-Soo Lim & Eun-Pyo Hong

To cite this article: Byeong-Kyu Lee , B. Raj Mohan , Seung-Hyeok Byeon , Kyung-Soo Lim & Eun-Pyo Hong (2013) Evaluating the performance of a turbulent wet scrubber for scrubbing particulate matter, Journal of the Air & Waste Management Association, 63:5, 499-506, DOI: 10.1080/10962247.2012.738626

To link to this article: https://doi.org/10.1080/10962247.2012.738626

TECHNICAL PAPER

Evaluating the performance of a turbulent wet scrubber for scrubbing particulate matter

Byeong-Kyu Lee,[1,*] B. Raj Mohan,[2] Seung-Hyeok Byeon,[1] Kyung-Soo Lim,[3] and Eun-Pyo Hong[4]

[1]*Department of Civil and Environmental Engineering, University of Ulsan, Ulsan, Korea*
[2]*National Institute of Technology Karanataka–Surathkal, Mangalore, India*
[3]*Energy Conservation Research Department, Clean Energy System Research Center, Korea Institute of Energy Research, Daejeon, Korea*
[4]*Clean & Green Tech, Ungchon-myun, Ulju-gun, Ulsan, Korea*
**Please address correspondence to: Byeong-Kyu Lee, Department of Civil and Environmental Engineering, University of Ulsan, Nam-gu, Ulsan 680-749, Korea; e-mail: bklee@ulsan.ac.kr*

A turbulent wet scrubber was designed and developed to scrub particulate matter (PM) at micrometer and submicrometer levels from the effluent gas stream of an industrial coal furnace. Experiments were conducted to estimate the particle removal efficiency of the turbulent scrubber with different gas flow rates and liquid heads above the nozzle. Particles larger than 1 μm were removed very efficiently, at nearly 100%, depending upon the flow rate, the concentration of the dust-laden air stream, and the water level in the reservoir. Particles smaller than 1 μm were also removed to a greater extent at higher gas flow rates and for greater liquid heads. Pressure-drop studies were also carried out to estimate the energy consumed by the scrubber for the entire range of particle sizes distributed in the carrier gas. A maximum pressure drop of 217 mm H_2O was observed for a liquid head of 36 cm and a gas flow rate of 7 m^3/min. The number of transfer units (NTU) analysis for the efficiencies achieved by the turbulent scrubber over the range of particles also reveals that the contacting power achieved by the scrubber is better except for smaller particles. The turbulent scrubber is more competent for scrubbing particulate matter, in particular $PM_{2.5}$, than other higher energy or conventional scrubbers, and is comparable to other wet scrubbers of its kind for the amount of energy spent.

Implications: The evaluation of the turbulent scrubber is done to add a novel scrubber in the list of wet scrubbers for industrial applications, yet simple in design, easy to operate, with better compactness, and with high efficiencies at lower energy consumption. Hence the turbulent scrubber can be used to combat particulate from industrial gaseous effluents and also has a scope to absorb gaseous pollutants if the gases are soluble in the medium used for particles capture.

Introduction

Wet scrubbers are effective at scrubbing both particulate and gaseous pollutants from effluent gas streams, and are also more economically viable than other particle control devices (Calvert et al., 1974; Chang and Ghorishi, 2006; Jin et al., 2006; Choi et al., 2007; Keshavarz et al., 2007; Chandrasekara Pillai et al., 2009). The liquid phase used to remove particulate matters is unique in its ability to remove both particulate and gaseous pollutants. Wet scrubbers are either gas-dispersed or liquid-dispersed systems (Meikap et al., 2002; Sarkar et al., 2007; Deshwal et al., 2008). Particles are collected by either liquid drops or a continuum of liquid. The creation of a thin film of liquid provides a blanketing effect to entrap particles (Drehmel, 1974). In the case of droplets being used to collect particles, impaction and interception are the two predominant mechanisms for removing particles (Pilate and Prem, 1977; Gemci and Ebert, 1992; Kim et al., 2001; Muller et al., 2001). Pilat et al. (1977) reported the effects of diffusiophoresis and thermophoresis on the efficiency of particle collection by spray droplets, and revealed that thermophorosis affects the collection efficiency more than diffusiophorosis does. It was also reported that diffusiophorosis contributes only 2% of overall collection efficiency and is applicable to particles of submicrometer levels (Schmidt and Löffler, 1992; Yoshida et al., 2005).

Many researchers have attempted to determine the critical mechanisms involved in particulate matter scrubbing and gas absorption by wet scrubbers (Miconnet et al., 1981; Haase and Koehne, 1999; Kashdan et al., 1982; Chien, and Chu, 2000). Jung and Lee (1998) were the first researchers to carry out an analytical study on the collection of small particles by a system consisting of multiple fluid spheres, such as water droplets or gas bubbles. Kim et al. (1992) were the first to carry out a theoretical analysis of the particle removal efficiency of a gravitational wet scrubber, taking into consideration diffusion, interception, and impaction. Park and Lee (2009) derived analytical solutions for the removal of a polydisperse aerosol by wet scrubbing, employing Brownian diffusion and inertial impaction as removal

Journal of the Air & Waste Management Association, 63(5):499–506, 2013. Copyright © 2013 A&WMA. ISSN: 1096-2247 print
DOI: 10.1080/10962247.2012.738626

mechanisms. Meikap et al. (2004) achieved a removal efficiency of 95% to 99% for particulate matter of sizes ranging from 0.1 μm to 100 μm in a modified multistage bubble column scrubber. Hence, spray columns and bubble column scrubbers are more convenient for scrubbing particulate matter from effluent. Cascading both systems in a series leads to very high efficiencies provided that the pressure losses are less. Raj Mohan et al. (2009) report a particulate removal efficiency of 99.32% for 5.0×10^{-3} kg/m^3 of solid loading in a spray column and bubble column scrubber (Bozorgi et al., 2006; Meikap et al., 2002; Raj Mohan et al., 2008). Thus, particles are conditioned during the scrubbing process by wetting them and entrapping them in water blankets, and by impaction with water droplets. Certain wet scrubbers, like turbulent wet scrubbers, involve both mechanisms in a single system in a compact mode of operation.

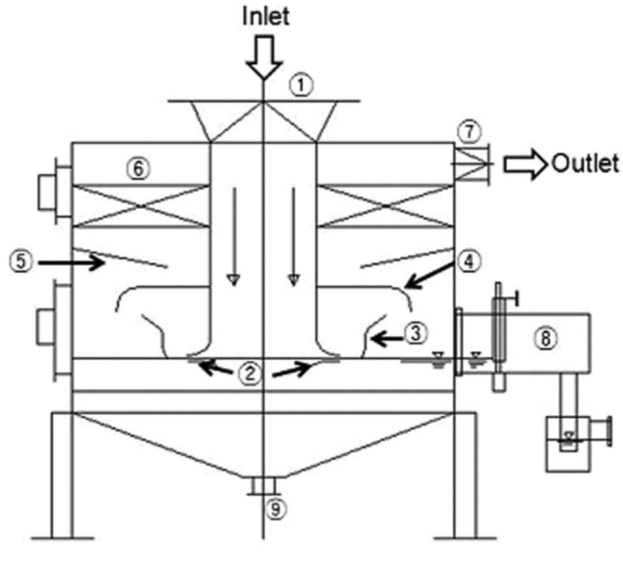
Raj Mohan et al. (2002) performed a comprehensive analysis for the prediction of dust removal efficiency using twin-fluid atomization in a spray scrubber. Their results revealed that particles smaller than 1 μm are difficult to remove using simple spray columns. Modern wet scrubbers aim for 100% removal of particles, including those at submicrometer levels. A detailed study on particulate scrubbing efficiency based on the aerodynamic diameter of the particles was performed by Lee et al. (2008) in their study on the development and application of a novel swirl cyclone scrubber. Furthermore, Park and Lee (2009) performed both experimental and theoretical research on the novel swirl cyclone scrubber.

Turbulent flow is a type of fluid (gas or liquid) flow in which the fluid undergoes irregular fluctuations or mixing. Thus, the air or water swirls and eddies while its overall bulk moves along a specific direction. In a multiphase flow turbulent scrubber, the particles carried by the gas bubbles interact with the continuous liquid flow and also with particles when the wake and bubble boundary layer overlap to form large bubbles. Pollock et al. (1966) reported on the application of a turbulent contact absorber for the absorption of SO_2 and simultaneous removal of fly ash in a coal-fired power plant, with a fly ash collection efficiency of 98% and overall SO_2 removal of 91% (Bandyopadhyay and Biswas., 2007; Díaz-Somoano et al., 2007). Typically, particles around 1 μm and below 1 μm (submicrometer) present in small amounts in the total particulate mixture have serious impacts on human health and the environment (Dullien and Spink, 1978). These particles are difficult to remove using any conventional scrubbers (Dullien and Spink, 1978; Dockery and Pope, 1994). The most critical particles are those in the 0.1 μm to 0.5 μm range, because they are the most difficult for wet scrubbers to remove. Hence, the present control methods for particulates focus on particles from 0.2 μm to 2.0 μm. The improved methods adopted for scrubbing these fine particles use separation forces that are "flux forces," like diffusiophoresis, thermophoresis, electrophoresis, and agglomeration, which make the scrubbing processes more effective.

In the present work, we designed and developed a turbulent scrubber to effectively remove dust particles arising from a coal-powered thermal power plant.

Development of the Turbulent Wet Scrubber

Figure 1 shows a schematic diagram of the turbulent wet scrubber (TWS) developed in this study. The vertical inlet pipe ends in the scrubbing chamber which contains liquid in two compartments, as shown in Figure 1. One chamber surrounds the nozzle at the center, and the other chamber is the rest of the tank. The inlet pipe has a curved nozzle so that the air discharge is in the lateral direction. The air stream from a blower mixed with particles first contacts the water surface in the reservoir and displaces the water. The stream is compressed when it passes through the nozzle, the size of which can be adjusted depending upon the water level. Having passed through the nozzle tip, the compressed air contains particles as it contacts the water in front of the deflectors. These water contacts mainly collect larger particles. Two deflectors as a pair are kept 10 cm from both sides (tips) of the nozzle (as shown in Figure 2), such that the lateral movement of the air stream carries the liquid upward in the presence of the deflector (impactor). This creates high turbulence due to the impaction and upward swirl motion. Two sets of deflectors are provided to create turbulence; one is attached to the inlet vertical pipe at the center, and one is attached on the periphery of the chamber 870 mm from the bottom of the section, as shown in Figure 2. Large amounts of particles are collected in the two deflector zones by creating turbulence mixing. The outside-curved configuration of the first deflector helps the flow of the stream. The unique design (inside-curved configuration) of the second deflector creates an effective contact between the scrubbing medium and particles, and prevents entrainment losses. The scrubbing medium (gas–liquid mixture) hits the second deflector and flows down, creating a water curtain that spans from the tip of the second deflector to the water head



Note: ① Inlet ② Nozzle ③ Deflector 1 ④ Deflector 2 ⑤ Baffle
⑥ Demister ⑦ Outlet ⑧ Water supply ⑨ Drain

Figure 1. A schematic diagram of the turbulent wet scrubber system.

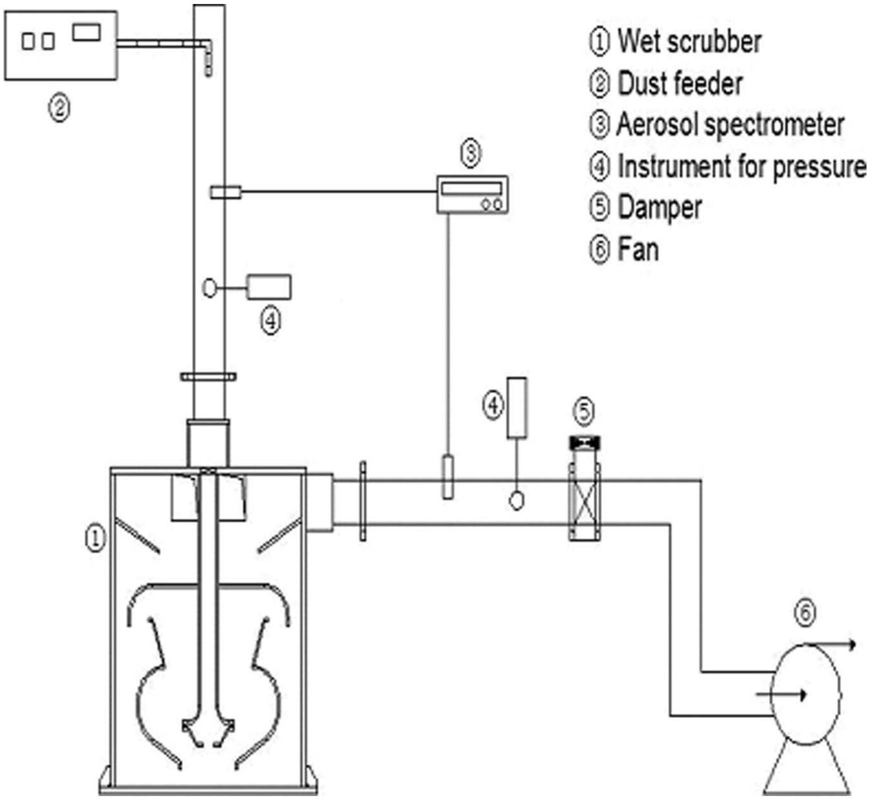


Figure 2. Schematic sketch for performance test of turbulent wet scrubber system.

in the reservoir. The water curtain can collect particles via impaction and interception. The air stream—which then contains particles, gases, and the scrubbing medium—passes through the zone in front of the gas and liquid separator, which collects liquids and particles and reduces the pressure loss at the following demister. After liquids and particles are collected in the separation zone, the remaining air stream passes through the demister to eliminate water mist and particles.

Experimental Procedures

Figure 2 represents a schematic sketch for a performance test of the TWS. The turbulent scrubber consists of a vertical inlet pipe at the center, through which the air and fly ash (as dust particles) enter the scrubber. The solid aerosol particle generator is connected to the inlet pipe to feed fly ash brought from a nearby thermal power plant at different concentrations. A portable aerosol spectrometer (portable dust monitor with 15 particle size channels, model 1.108, Grim, Germany) is connected to the inlet and outlet pipes of the scrubber to measure the particle concentrations and size distribution. A Testo 350–S/XL (Germany) is used to measure the pressure loss across the scrubbing section of the turbulent scrubber.

The three selected parameters that affect particle collection efficiency are the input concentration of particulate matter, the water level in the water reservoir of the TWS, and the flow rate of the air stream. The particulate scrubbing process in the turbulent wet scrubber was carried out for three different water levels filled through the opening of the nozzle from the water reservoir. The air stream at different flow rates (5.13 m^3/min and 7.62 m^3/min) and containing different input concentrations of particulate matter (230.84 mg/min, 110.89 mg/min, and 48.78 mg/min) was prepared with the aerosol feeder by adjusting feed rates to 10, 5, and 2, respectively. The air stream was then fed into the turbulent scrubber system. Fly ash was used to adjust concentrations of particulate matter in the air stream. The fly ash obtained from a coal power plant is a powder type with a spherical shape, and its major components are alumina (Al_2O_3) and silica (SiO_2). The fly ash has an average diameter of 20–30 μm, an apparent density of 800–1000 kg/m^3, and a true specific weight of 1.9–2.3. The dust-laden gas enters the scrubbing chamber by displacing the water in the vertical inlet pipe, and passes through a small rectangular nozzle of dimensions 760 mm × 25 mm to a horizontal exit parallel to the liquid surface in the inner compartment of the scrubber. The water level of the scrubber is varied between 0 cm, 32 cm, 34 cm, and 36 cm from the bottom of the water reservoir. The lateral movement of the gas stream at the surface of the water for the first level (0 cm) scours the water surface and throws the particulate matter onto the deflectors, thereby creating agitation in the water column. At higher gas flow rates, the gas passing through the nozzle exits at high velocities, leading to vigorous agitation of the liquid and throwing of particular matter onto the curved deflector. The liquid climbs upward in the curved deflector and falls back to the bulk liquid, enclosing the gas in the form of bubbles. Thus, heavy turbulence is created by the gas stream in the stagnant water within the curved deflectors. For liquid levels of 32, 34, and 36 cm, the exit of gas from the nozzle leads to very high turbulence and results in a homogeneous gas and liquid mixture in the scrubber. This homogeneous gas and liquid mixture rises quickly and overflows above the deflectors to the rest of the chamber through the upper part of the deflector, as shown in Figure 2. Significant turbulence is created by gas bubbles formed in the rest of the chamber due to falling of the homogeneous medium. Thus, the entire scrubbing chamber is kept under turbulence and performs the particulate scrubbing process effectively. The downward-curved deflector prevents the entrainment of fine liquid droplets that arise due to bursting of the bubbles at the surface of the liquid.

Results and Discussion

Pressure-drop studies

Turbulent wet scrubbers are high-energy scrubbers. High energy is utilized at the expense of gas- or liquid-phase energy to create turbulence in the scrubbing section for more efficient scrubbing. The turbulent scrubber used in the present study utilizes gas-phase energy in the form of high-velocity gas to displace the liquid in the inlet pipe and create turbulence in the scrubbing chamber. The pressure drop in the turbulent scrubber depends on the gas flow rates, the nozzle dimensions, and the liquid heads above the nozzle. The initial water level in the water reservoir was kept just below the nozzle (0 cm) and the pressure drop was measured for different gas flow rates. This pressure drop indicates the energy spent by the gas medium in scouring the liquid from the surface into films and droplets, and thereby creating turbulence for scrubbing. The pressure drop is due to the liquid head above the nozzle, and is measured at different gas flow rates for liquid levels of 32 cm, 34 cm, and 36 cm from the bottom of the reservoir.

Figure 3 shows the effect of the gas flow rate on the pressure drop in the turbulent scrubber. As the gas flow rate increases, the pressure drop also increases. The pressure drop of fluid flowing across a system is directly proportional to the square of its velocity. Figure 3 also shows that there is a significant difference between the pressure drops across the turbulent scrubber with and without the liquid level above the nozzle. The pressure drop without the liquid is less than 20 mm H_2O for the given gas flow rates, and it increases gradually along with the gas flow rate. The pressure drop across the nozzle is dominant compared to the liquid volume that is scoured upward in the deflector in the homogeneous form. Hence, the pressure drop is minimal compared to the pressure across the nozzle with the liquid head. The pressure drop for the system with a water head above the nozzle shows a different trend than the system with a pressure drop without a liquid head. The pressure drop increases steeply for gas flow rates up to 5 m^3/min. Above 5 m^3/min, the pressure drop increases gradually to reach a saturation level.

The ratio of energy spent in creating turbulence is greater than at lower gas flow rates than at high flow rates, even though more liquid is kept under turbulence. Figure 4 shows the effect of the liquid level on the pressure drop. As the liquid head increases, the energy spent in homogenizing the liquid increases. Hence, there is a steep increase in the pressure drop with respect to the liquid level in the system. Figure 4 also reveals that the pressure

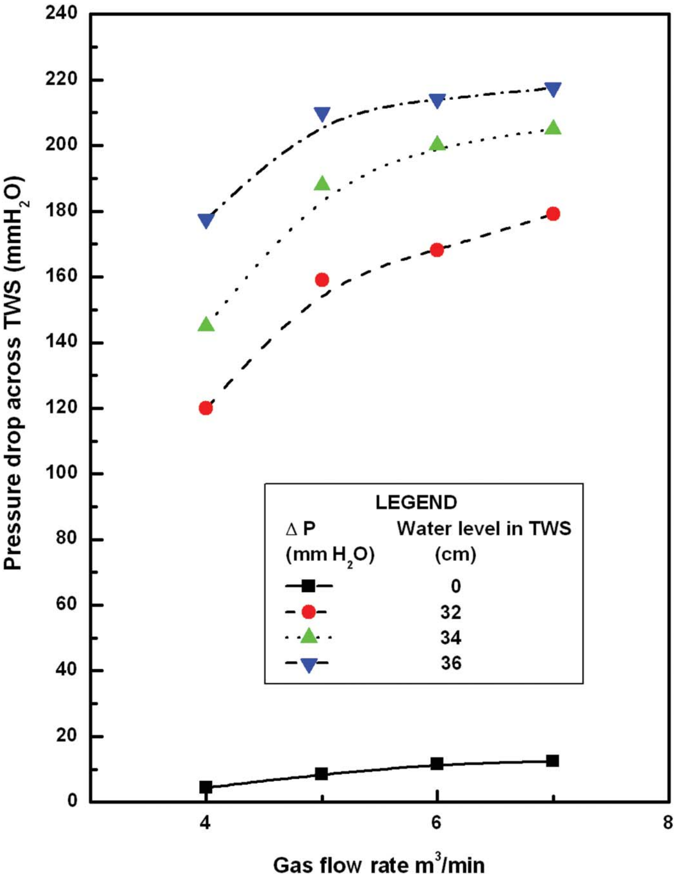


Figure 3. Effect of gas flow rate on pressure drop in the turbulent wet scrubber (color figure available online).

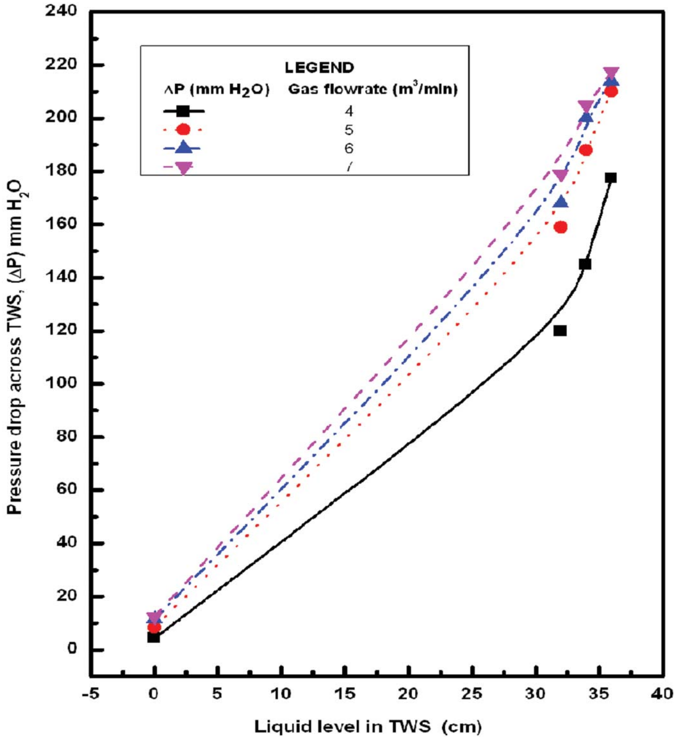


Figure 4. Effect of liquid level on pressure drop in the turbulent wet scrubber (color figure available online).

drop increases along with the gas flow rate due to the hydrostatic head above the nozzle and frictional losses.

Effects of particle size on efficiency at different liquid levels

In wet scrubbing, fine particles are scrubbed mainly under the influence of flux forces. In turbulent scrubbers, these flux forces aid in scrubbing the particulate matter. As the particle size (fly ash) increases from 0.65 μm, the efficiency of the turbulent scrubber increases and reaches almost 100% for particles around 5 μm (Figure 5). For a water level of 32 cm in the scrubber, the efficiency is around 43%. For water heads of 34 cm and 36 cm above the nozzle, the scrubbers reach efficiencies above 52% and 53%, respectively. There is a significant difference in particle scrubbing efficiency (ranging from 5% to 9%) for liquid heads between 32 cm and 34 cm in the scrubber for particles in the range between 0.65 μm and 1.0 μm, whereas for particles larger than 1.0 μm, the efficiency is almost the same for all liquid levels. The difference in percentage may be small, but it counts as the sizes of the particles are around the submicrometer level. Thus, liquid levels of 34 cm and 36 cm above the nozzle have a scrubbing efficiency more than 50% better for the smaller particles, even those ranging from 0.65 μm to 0.8 μm.

Effects of gas flow rate on particle removal efficiency

Higher gas velocities lead to more turbulence in the scrubber, resulting in higher scrubbing efficiencies. Higher gas velocities also result in greater pressure drops in turbulent scrubbers. Figure 6 shows the particle removal efficiency of the turbulent scrubber at two different gas flow rates. For the higher gas flow rate, the efficiency of the turbulent scrubber is found to be predominant for submicrometer particles. Thus, there is a marked difference in the particle removal efficiency of the turbulent scrubber for particles smaller than 1 μm. The efficiency curves for the two gas flow rates merge with each other for larger particles, indicating that turbulence effects due to different gas flow rates do not affect the efficiency substantially in the case of particles larger than 2 μm. Thus, the contact between the gas and liquid for particle removal is established well for larger particles even at low gas flow rates, and the efficiency almost reaches

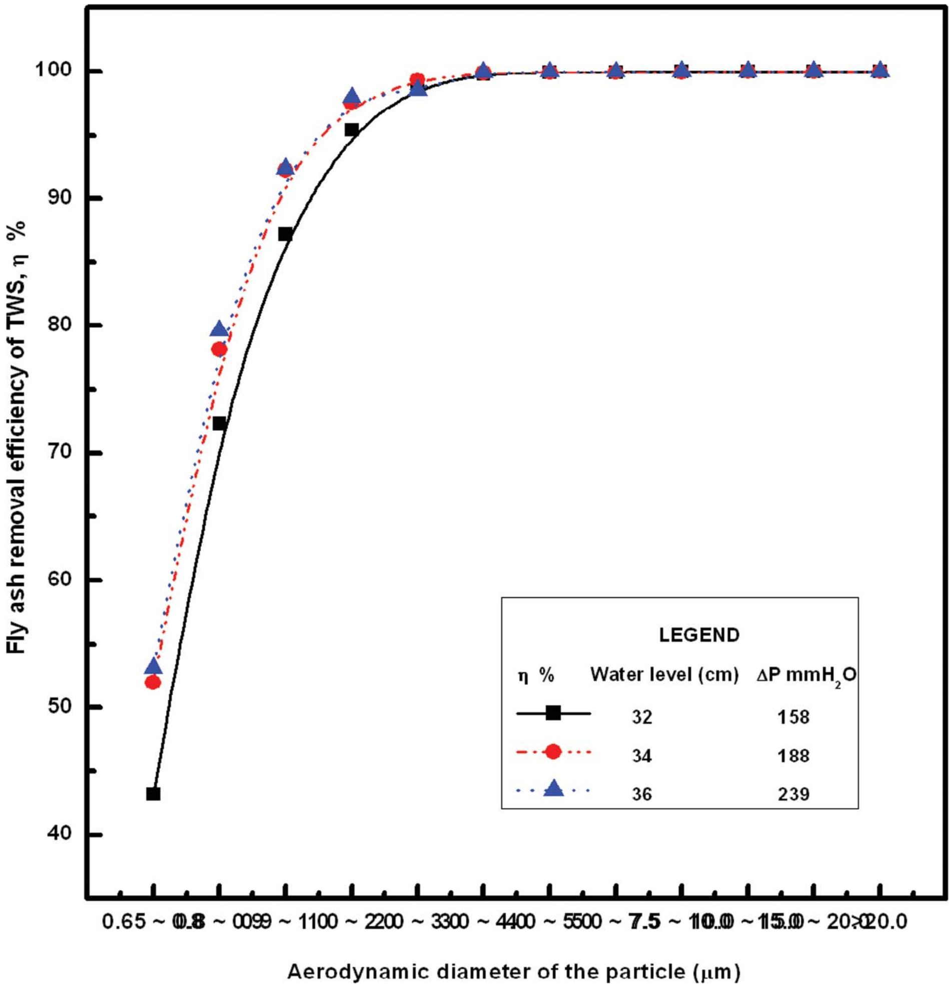


Figure 5. Effect of particle size on the efficiency of the turbulent wet scrubber (color figure available online).

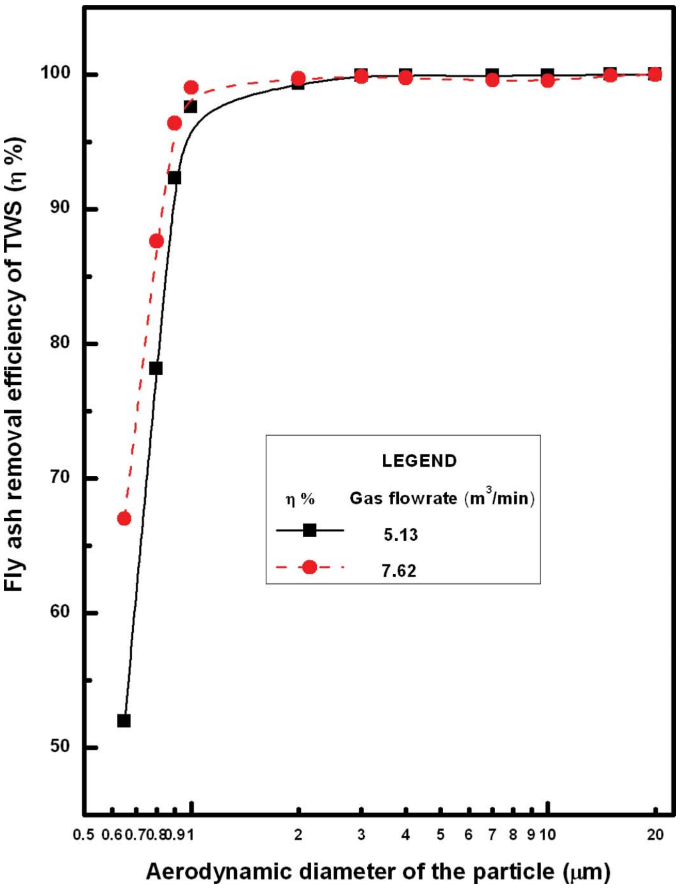


Figure 6. Efficiency of turbulent wet scrubber for definite particle sizes at different gas flow rates (color figure available online).

100%. A plot relating the pressure drop to the scrubbing efficiency gives insight into the energy spent in achieving the range of efficiencies for the given size distribution of particles.

Effects of energy consumption on particle removal efficiency

A correlation analysis for predicting particulate removal efficiency in the turbulent scrubber with respect to the energy spent was carried out by utilizing the contacting power theory approach. This approach predicts the size distribution of droplets or bubbles for different gas flow rates in the case of a turbulent scrubber in which the gas–liquid mixture is a homogeneous medium. Since the turbulent wet scrubber developed in this study falls between the droplet and bubble scrubber categories, the scrubbing efficiency can be directly associated with the energy spent in creating the turbulence in the system. Lapple and Kamack (1995) show that in wet scrubbing design, efficiency can be related to the energy expended in producing the actual gas–liquid contact. Thus, the contact power is the energy dissipated per unit volume of gas treated, which can be estimated from the total pressure drop in the turbulent scrubbing system. In the present turbulent scrubber, the energy spent in scrubbing is totally from the gas side. According to Semaru (1963), the efficiency (η) of a wet scrubber is related to the number of transfer units, as shown in the following:

$$\eta = 1 - \exp(-N_t) \tag{1}$$

where N_t is the number of transfer units (NTU) and is related to the pressure drop in terms of the contacting power as given next:

$$N_t = \alpha(P_T)^{\gamma} \tag{2}$$

where P_T is the contacting power (kW/1000 m^3), α the coefficient of expansion, and γ the exponent of P_T (dimensionless).

A plot of N_t versus P_T on a logarithmic scale yields the slope and the intercept. Figure 7 shows a plot of N_t versus P_T, and the values of α and γ are given in Table 1. As the contacting power increases, the number of transfer units also increases. This is because the number of transfer units for a compact turbulent scrubber is an interpretation of efficiencies. The plot of efficiency versus contacting power illustrates this point. The values of the slope γ are almost the same for all particle sizes ranging from 0.72 μm to 5 μm.

The contacting power is low for particles larger than 1 μm. The contact power is the same for particles around 1 μm in the turbulent scrubber and it increases along with the liquid levels and gas flow rates. As the particle size increases, the N_t values increase due to high efficiencies. The contact between large particles in the gas with liquid may be high, resulting in high scrubbing efficiencies compared to smaller or submicrometer

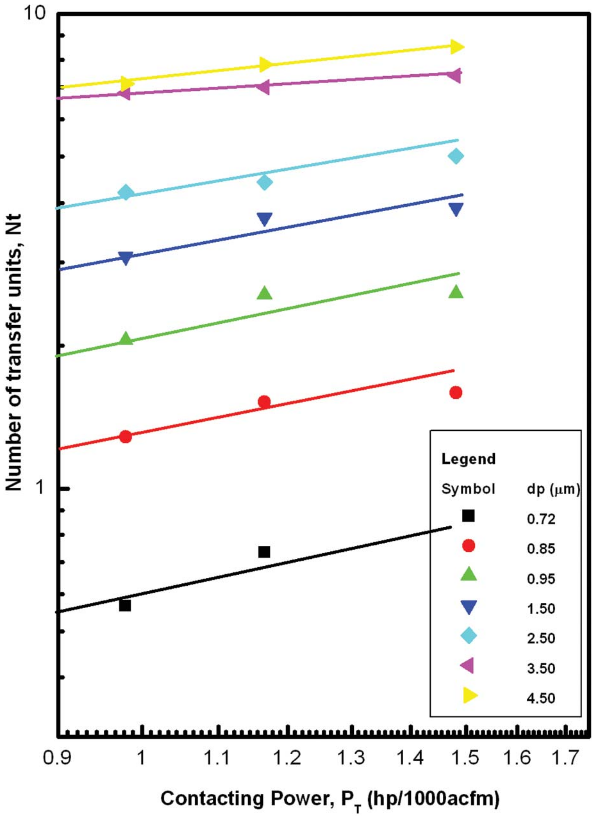


Figure 7. Correlation between number of transfer units and contacting power (color figure available online).

Table 1. Data describing scrubbing efficiency, number of transfer units, and contacting power in the TWS

d_p (μm)	Efficiency	P_t	N_t	Slope (γ)	Intercept (α)
0.72	0.4321	0.979724	0.56581	0.6618	−0.5031
	0.5196	1.165748	0.733136		
	0.5300	1.481988	0.755023		
0.85	0.7234	0.979724	1.285183	0.4975	0.2911
	0.7814	1.165748	1.520512		
	0.7965	1.481988	1.592089		
0.95	0.8722	0.979724	2.057289	0.5124	0.7796
	0.9228	1.165748	2.561356		
	0.9240	1.481988	2.577022		
1.5	0.9539	0.979724	3.076942	0.5512	1.1694
	0.9757	1.165748	3.717279		
	0.9798	1.481988	3.902073		
2.5	0.9881	0.979724	4.431217	0.5152	1.5412
	0.9934	1.165748	5.020686		
	0.9953	1.481988	5.219908		
3.5	0.9989	0.979724	6.812445	0.2077	1.9204
	0.9991	1.165748	7.013116		
	0.9994	1.481988	7.418581		
4.5	0.9992	0.979724	7.130899	0.4246	1.9801
	0.9996	1.165748	7.824046		
	0.9998	1.481988	8.517193		

particles for the same energy expended or contacting power. Table 1 reveals that the value of N_t increases gradually with increases in the value of P_t, and the order of increase is similar for particles around 1 μm, as indicated by the slope of a linear plot of Nt versus Pt on a log–log scale. Figure 8 shows a comparison graph of particulate scrubbing with different scrubbers, including the turbulent wet scrubber. The dotted lines represent the efficiency of the turbulent scrubber with respect to the aerodynamic diameters of the particles. Except for particles smaller than 0.95 μm, the turbulent scrubber is nearly as efficient as high-energy scrubbers, such as the venture scrubber, electrostatic precipitator, and bag-house filters. Thus, the turbulent wet scrubber is a competent wet scrubber for scrubbing particulate matter.

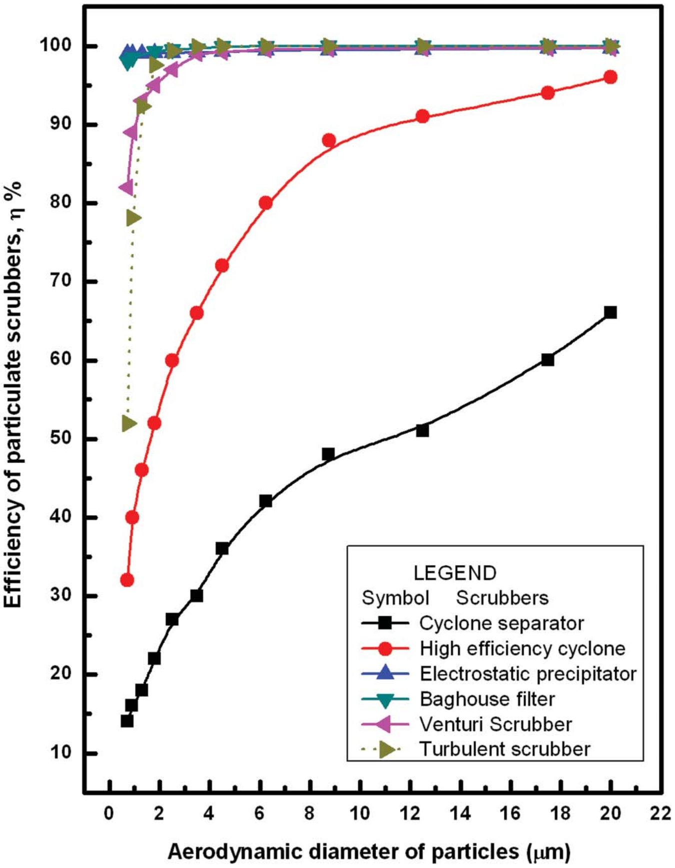


Figure 8. Comparison of particle removal efficiencies of different scrubber types with turbulence (color figure available online).

References

Bandyopadhyay, A., and M.N. Biswas. 2007. Fly ash scrubbing in a novel dual flow scrubber. *Waste Manage*. 27:1845–1859. doi:10.1016/j.wasman.2006.10.013

Bozorgi, Y., P. Keshavarz, M. Taheri, et al., 2006. Simulation of a spray scrubber performance with Eulerian/Lagrangian approach in the aerosol removing process. *J. Hazard. Mater*. 137:509–517. doi:10.1016/j.jhazmat.2006.02.037

Calvert. S., J. Goldshmid, D. Leith. 1974. Scrubber Performance for Particle Collection. *AIChE Symposium Series* 72:357–364.

Chandrasekara Pillai, K., S.J. Chung, T. Raju, et al. 2009. Experimental aspects of combined NO_x and SO_2 removal from flue-gas mixture in an integrated wet scrubber–electrochemical cell system. *Chemosphere* 76:57–664. doi:10.1016/j.chemosphere.2009.04.013

Chang J.C.S., and S.B. Ghorishi. 2003. Simulation and evaluation of elemental mercury concentration increase in flue gas across a wet scrubber. *Environ. Sci. Technol*. 37:5763–5766. doi:10.1021/es034352s

Chien, T.-W., and H. Chu. 2000. Removal of SO_2 and NO from flue gas by wet scrubbing using an aqueous $NaClO_2$ solution. *J. Hazard. Mater*. 80:43–57. doi:10.1016/S0304-3894(00)00274-0

Choi, K.-I., and D.-H. Lee. 2007. PCDD/DF concentrations at the inlets and outlets of wet scrubbers in Korean waste incinerators. *Chemosphere* 66:370–376. doi:10.1016/j.chemosphere.2006.04.094

Deshwal, B.R., D.S. Jin, S.H. Lee, et al. Removal of NO from flue gas by aqueous chlorine-dioxide scrubbing solution in a lab-scale bubbling reactor. *J. Hazard. Mater*. 150:649–655. doi:10.1016/j.jhazmat.2007.05.016

Díaz-Somoano, M., S. Unterberger, and K.R.G. Hein. 2007. Mercury emission control in coal-fired plants: The role of wet scrubbers. *Fuel Process. Technol*. 88:259–263. doi:10.1016/j.fuproc.2006.10.003

Dockery, D.W., and C.A. Pope. 1994. Acute respiratory effects of particulate air pollution. *Annu. Rev. Public Health* 15:107–132. doi:10.1146/annurev.pu.15.050194.000543

Drehmel, D.C. 1974. Fine Particle Scrubber Symposium, Report PB-239335. Research Triangle Park, NC: U.S. Environmental Protection Agency.

Dullien, F.A.L., and D.R. Spink. 1978. In *The Waterloo Scrubber Part I: The Aerodynamic Capture of Particles*. Proceedings of International Symposium in Waste Treatment and Utilization, Theory and Practice of Waste Management, 467–486. Waterloo, Ontario, Canada: Pergamon Press.

Gemci, T., and F. Ebert. 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. *J. Aerosol Sci*. 23:769–772. doi:10.1016/0021-8502(92)90525-Z

Haase, F., and H. Koehne. 1999. Design of scrubbers for condensing boilers. *Prog. Energy Combust. Sci*. 25:305–337. doi:10.1016/S0360-1285(99)00002-7

Jin, D.S., B.R. Deshwal, Y.S. Park, et al. 2006. Simultaneous removal of SO_2 and NO by wet scrubbing using aqueous chlorine dioxide solution. *J. Hazard. Mater*. 135:412–417. doi:10.1016/j.jhazmat.2005.12.001

Jung, C.H., and K.W. Lee. 1998. Filtration of fine particles by multiple liquid droplet and gas bubble systems. *Aerosol Sci. Technol*. 29:389–401. doi:10.1080/02786829808965578

Kashdan, E.R., B.R. Madhav., D.L. Harmon. 1982. Design guidelines for an optimum scrubber system. *Environ. Int*. 6:11–20. doi:10.1016/0160-4120(81)90004-0

Keshavarz, P., Y. Bozorgi, J. Fathikalajahi, et al. 2008. Prediction of the spray scrubbers' performance in the gaseous and particulate scrubbing processes. *Chem. Eng. J*. 140:22–31. doi:10.1016/j.cej.2007.08.034

Kim, H.T., C.H. Jung, S.N. Oh, et al. 2001. Particle removal efficiency of wet gravitational scrubber considering impaction, interception, diffusion. *Environ. Eng. Sci*. 18:125–136. doi:10.1089/10928750151132357

Lapple, C.E., and H.J. Kamack. 1955. Performance of wet dust scrubbers. *Chem. Eng. Progress*. 51:110–121.

Lee, B.-K., K.R. Jung, S.H. Park. 2008. Development and application of a novel swirl cyclone (1)—Experimental. *J. Aerosol Sci*. 39:1079–1088. doi:10.1016/j.jaerosci.2008.07.010

Meikap, B.C., G. Kundu, M.N. Biswas. 2002. Scrubbing of fly-ash laden SO_2 in modified multistage bubble column scrubber. *AIChE J*. 48:2074–2083. doi:10.1002/aic.690480920

Meikap, B.C., G. Kundu, M.N. Biswas. 2002. Modeling of a novel multi-stage bubble column scrubber for flue gas desulfurization. *Chem. Eng. J*. 86(3): 331–342. doi:10.1016/S1385-8947(01)00226-1

Meikap, B.C., and M.N. Biswas. 2004. Fly-ash removal efficiency in a modified multi-stage bubble column scrubber. *Separ. Purif. Technol*. 36:177–190. doi:10.1016/S1383-5866(03)00213-2

Miconnet, A., P. Guigon, J.F. Large. 1981. Hydrogen chloride absorption in a turbulent contact scrubber. *Chem. Eng. J*. 22:143–149. doi:10.1016/0300-9467(81)80032-9

Muller, N., B. Benadda, M. Otterbein. 2001. Mass transfer in a droplet column in presence of solid particles. *Chem. Eng. Process*. 40:167–174. doi:10.1016/S0255-2701(00)00136-7

Park, S.H., and B.K. Lee. 2009. Development and application of a novel swirl cyclone (2)—Theoretical. *J. Hazard. Mater*. 39:1079–1088. doi:10.1016/j.jhazmat.2008.08.023

Pilate, M.J., and A. Prem. 1977. Effect of diffusiophoresis and thermophoresis on the overall particle collection efficiency of spray droplet scrubbers. *J. Air Pollut. Control Assoc*. 27:982–988. doi:10.1080/00022470.1977.10470521

Pollock, W.A., J.P. Tomany, G. Frieling. 1966. Removal of SO_2 and fly ash from coal burning power plant flue gas. ASME Meeting. November 27 - December 1, New York, NY.

Raj Mohan, B., S. Biswas, B.C. Meikap. 2008. Performance characteristics of the particulates scrubbing in a counter-current spray-column, *Sep. Purif. Technol*. 61:96–102. doi:10.1016/j.seppur.2007.09.018

Raj Mohan, B., and B.C. Meikap. 2009. Performance studies of the particulate scrubbing in a novel spray-cum-bubble column scrubber. *Chem. Eng. Res. Design*. 87:109–118. doi:10.1016/j.cherd.2008.05.011

Sarkar, S., B.C. Meikap, S.G. Chatterjee. 2007. Modeling of removal of sulfur dioxide from flue gases in a horizontal cocurrent gas–liquid scrubber. *Chem. Eng. J*. 131:263–271. doi:10.1016/j.cej.2006.12.013

Schmidt, M., and F. Löffler. 1992. Investigations on fine particle separation using an electrostatic nozzle scrubber. *J. Aerosol Sci*. 23:773–777. doi:10.1016/0021-8502(92)90526-2

Semrau, K.T. 1963. Dust scrubber design—A critique on the state of the art. *J. Air Pollut. Control Assoc*. 13:587–593. doi:10.1080/00022470.1963.10468224

Yoshida, H., K. Ono, K. Fukui. 2005. The effect of a new method of fluid flow control on submicron particle classification in gas-cyclones. *Powder Technol*. 149:139–147. doi:10.1016/j.powtec.2004.10.005

About the Authors

Byeong-Kyu Lee is a professor of Civil and Environmental Engineering, Director of Brain Korea 21, and Vice Director of Foundation for Industry Cooperation at the University of Ulsan, Ulsan, Korea.

B. Raj Mohan is an assistant professor of Civil Engineering at the National Institute of Technology Karanataka–Surathkal, Mangalore, India.

Seung-Hyeok Byeon is an assistant manager of SMP Ltd., Ulsan, Korea.

Kyung-Soo Lim was a researcher of Energy Conservation Research Department, Clean Energy System Research Center, Korea Institute of Energy Research, Daejeon, Korea.

Eun-Pyo Hong is the CEO of Clean & Green Tech, Ungchon-myun, Ulju-gun, Ulsan, Korea.