Control Efficiency of Submicron Particles by an Efficient Venturi Scrubber System

Cheng-Hsiung Huang[1]; Chuen-Jinn Tsai[2]; and Yu-Min Wang[3]

Abstract: An efficient venturi scrubber system combining a particle growth device and a traditional venturi scrubber was designed and tested in the laboratory. Before the venturi scrubber, saturated steam at 100°C was mixed with normal temperature waste stream to achieve supersaturation conditions allowing submicron particles to grow into micron sizes. Hence the control efficiency of submicron particles was greatly enhanced at a reasonably low pressure drop as compared to that found in the literature. At a flow rate of 250 L/min and a liquid to gas ratio of 2.5 L/m^3, the control efficiency of the present venturi scrubber system for NaCl particles greater than 100 nm is greater than 90%, and pressure drop is only about 44 cmH_2O (4.3 kPa). In comparison, to remove only 50% of 0.6 μm particles at the same liquid to gas ratio, the pressure drop needed will be greater than 200 cmH_2O (or 19.6 kPa). Theoretical calculation has also been conducted to simulate particle growth process and the control efficiency of the venturi scrubber considering the effects of mixing ratio (ratio of steam to waste stream by mass flow rate) and particle diameter. Theoretical results using Calvert's theory (1970) were found to agree well with the experimental data for NaCl particles greater than 50 nm, and for SiO_2 particles greater than 150 nm.

DOI: 10.1061/(ASCE)0733-9372(2007)133:4(454)

CE Database subject headings: Air pollution; Control methods; Particles; Laboratory tests.

Introduction

The venturi scrubber is one of the most effective pieces of particle control equipment with low capital investment and maintenance cost (Boll 1973). The device is simple and easy to operate, and does not take too much space. To remove particles greater than 1.0 μm, the pressure drop of the scrubber is reasonable. However, to remove submicron particles, operating pressure drop (or running cost) is excessively high. For example, to achieve a cutoff aerodynamic diameter as low as 0.5 μm, pressure drop must be greater than 200 cmH_2O (or 19.6 kPa) when the liquid to gas ratio is 1.0 L/m^3 (Calvert 1977). Because of high operation cost, venturi scrubbers are not as popular as baghouses or electrostatics precipitators for submicron particle control. However, in some circumstances venturi scrubbers are better choices than the other two control devices. For example, in the semiconductor industry, fine particles generated in the process chambers or high-temperature local scrubbers are usually not treated efficiently (Hayes and Woods 1996). Sometimes, they become sources of white smoke emission (Tsai et al. 1997). Because of coexisting combustible residual gases, the industry cannot use electrostatic precipitators to control fine particles. Baghouses are not used widely in the industry either because of their large space requirement. Therefore it is desirable to have an efficient venturi scrubber that is able to remove submicron particles without the risks of fire hazard or explosion.

In the literature, the rate of fine particle growth in a supersaturated atmosphere of water vapor was studied both theoretically and experimentally (Yoshida et al. 1976). The results showed that the rate of particle growth undergoing condensation was very rapid, and that the volume-mean diameter of grown particles was determined by the number concentration of particles and the initial state of supersaturation in the surrounding gas. An efficient multistage process that removed a wide range of fine particles assisted by the nucleation method has been investigated and discussed by Chen and Wu (1992) and Chen et al. (1993). In their methods, exhaust gas stream was mixed with supersaturated steam in a chamber, where water vapor was condensed on particles which further grew to bigger sizes in a cooling chamber. The grown particles were removed by a cyclone after the gas flow was accelerated through a nozzle. These investigators showed that steam mixing and subsequent cooling methods were effective to increase fine particle control efficiency.

In this study, we used saturation steam at 100°C for fine particle growth before particles enter the venturi scrubber system. Submicron particles will grow due to heterogeneous nucleation and condensation to micron sizes, and are removed efficiently by the venturi scrubber. Based on the numerical results, the mixing ratio (defined as the ratio of steam to waste stream mass flow rate) around 0.1 was used for particle growth. NaCl and SiO_2 particles were generated in the laboratory to test the control efficiency of the venturi scrubber system. The influence of the liquid to gas ratio and gas flow rate on the fine particle control efficiency was investigated experimentally. Theoretical calculation was also con-

[1]Associate Professor, Dept. of Environmental Engineering and Health, Yuanpei Univ., No. 306, Yuanpei St., 300 HsinChu, Taiwan. E-mail: chhuang@mail.ypu.edu.tw

[2]Professor and Chairman, Institute of Environmental Engineering, National Chiao Tung Univ., No. 75, Poai St., Hsinchu, 300, Taiwan (corresponding author). E-mail: cjtsai@mail.nctu.edu.tw

[3]Ph.D. Student, Institute of Environmental Engineering, National Chiao Tung Univ., No. 75, Poai St., Hsinchu, 300, Taiwan. E-mail: ymwang@mail.nctu.edu.tw

Note. Discussion open until September 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on November 3, 2004; approved on September 19, 2006. This paper is part of the ***Journal of Environmental Engineering***, Vol. 133, No. 4, April 1, 2007. ©ASCE, ISSN 0733-9372/2007/4-454–461/$25.00.

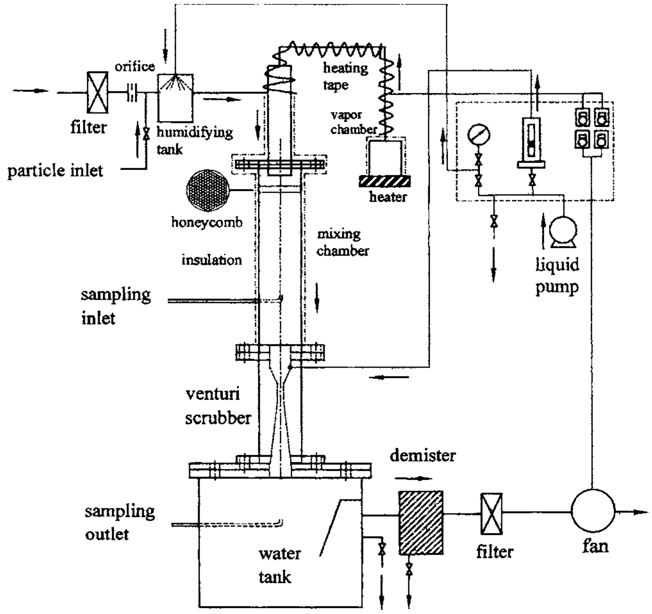

Fig. 1. Schematic diagram of the experimental system

ducted to simulate particle control efficiency, and the theoretical results were compared with the experimental data of the present study.

Experimental Methods

A venturi scrubber system was built and tested for measuring the control efficiency of submicron particles. Fig. 1 illustrates the schematic diagram of the experimental system and Fig. 2 shows the details of the venturi used in this study. The diameter of the throat is 1 cm and its length is 3 cm. The liquid of the venturi scrubber is injected tangentially at the entry of the throat. The gas flow rate passing through the venturi scrubber is 200, 250, and 300 L/min, respectively, and the liquid to gas ratio is 1.5, 2.0, and 2.5 L/m^3, respectively. The gas velocity is 42.4–63.7 m/s at the throat corresponding to the gas flow rate of 200–300 L/min. Tested particles including NaCl and SiO_2 were generated by a Constant Output Atomizer (TSI Model 3076), which were humidified by fine water spray and then mixed with saturated steam at 100°C to create supersaturation condition. Steam at higher temperature and pressure was not used since it increases mixed temperature and does not result in higher supersaturation condition. Aerosol particles grown by heterogeneous nucleation are removed by the downstream venturi scrubber. The steam to waste stream mass flow rate (or mixing ratio) is 0.10 ± 0.02 and 0.097 ± 0.015 for NaCl and SiO_2 particles, respectively, and initial mixed gas temperature is 58.3 ± 2.0 and 57.5 ± 4.8°C for NaCl and SiO_2 particles, respectively. A scanning mobility particle sizer (SMPS, TSI, Model 3934) system was used to measure the particle control efficiency of the venturi scrubber. It consists of an electrostatic classifier (EC, TSI, Model 3071), a condensation particle counter (CPC, TSI, Model 3022), and computer software.

The sampling tubes of the SMPS were placed at both the inlet and the outlet of the venturi scrubber for the size distribution measurement of fine particles ranging from 50 to 478 nm in diameter. The control efficiency of a certain particle size is calculated from the difference between the outlet and inlet number concentrations divided by the inlet number concentration. One data point at a particular test condition and particle size is the average of six to eight efficiency measurements, whereas each measurement consists of ten particle concentration readings at the inlet and the outlet, respectively. The particle control efficiency of the venturi scrubber is also determined when the saturated steam is turned off, simulating the case of the traditional venturi scrubber. A differential pressure gauge was also set up to measure the pressure drop of the venturi scrubber.

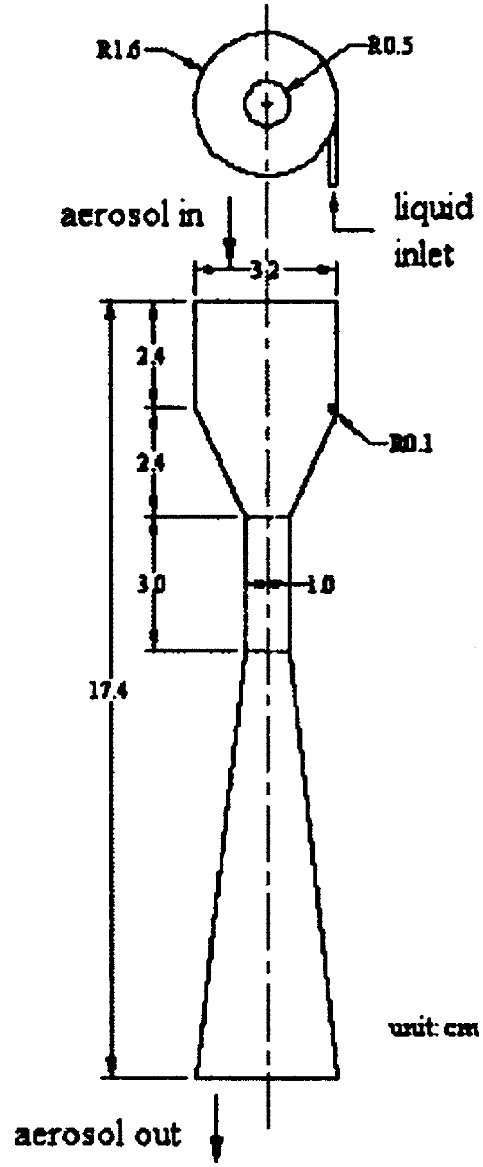

Fig. 2. Details of the venturi

Theory

State of Mixed Gas

Theoretical calculation was conducted to investigate the thermodynamic state of mixed gas and fine particle control efficiency of the venturi scrubber. When saturation steam is mixed with waste stream, the mixing ratio (or the ratio of the steam to waste stream by mass flow rate) can be expressed as follows:

J. Environ. Eng. 2007.133:454-461.

$$\text{mixing ratio} = \frac{M_{w2}}{M_{a1}(1+w_1)} \quad (1)$$

where M_{a1} (kg/s) represents the mass flow rate of dry air in the waste stream; M_{w2} (kg/s) = mass flow rate of steam; and w = absolute humidity of waste stream (subscript "1").

After mixing, the absolute humidity of mixed gas, w_3, can be expressed as follows:

$$w_3 = \frac{M_{a1}}{M_{a3}}w_1 + \frac{M_{w2}}{M_{a3}} = \frac{M_{a1}}{M_{a1}+M_{a2}}w_1 + \frac{M_{w2}}{M_{a1}+M_{a2}} \quad (2)$$

where M_{a2} (kg/s) and M_{a3} (kg/s) = mass flow rate of dry air in the water vapor and in the mixed gas, respectively.

The temperature (K) of mixed gas can be derived from the energy balance equation to be

$$T_3 = \frac{M_{a1}(C_{pa}+w_1C_{pg})T_1 + M_{w2}C_{pg}T_2}{M_{a1}(C_{pa}+w_1C_{pg}) + M_{w2}C_{pg}} \quad (3)$$

where C_{pa} (1002.1 J/kg K) and C_{pg} (1762.1 J/kg K) = specific heat of air and water vapor, respectively. T_1 (K) and T_2 (K) are the temperature of waste stream and saturated steam, respectively.

After mixing, the saturation ratio, S, can be derived from the following:

$$S = \frac{w_3P_mV_g}{R_aT_3 + w_3P_sV_g} = \frac{w_3P_mV_g}{(R_a + w_3R_g)T_3} \quad (4)$$

where R_a (286.99 J/kg K) = gas constant of air; and R_g (461.50 J/kg K) = gas constant of water vapor. P_m (Pa) = total pressure; P_s (Pa) = saturation pressure of water vapor at temperature T_3; and V_g (m^3/kg) = specific volume of water vapor at temperature T_3.

Particle Growth

The variation of particle diameter with time can be described by (Fuchs and Sutugin 1971)

$$\frac{dD_p}{dt} = \frac{4DM_w}{R\rho_wD_p}\left(\frac{P_\infty}{T} - \frac{P_d}{T_d}\right)\left(\frac{0.75\alpha(1+\mathrm{Kn})}{0.75\alpha + 0.283\,\mathrm{Kn}\,\alpha + \mathrm{Kn} + \mathrm{Kn}^2}\right) \quad (5)$$

The partial pressure of water vapor on the particle surface, P_d (Pa), can be expressed as

$$P_d = P_s\left(1 + \frac{6imM_w}{M_s\rho_w\pi D_p^3}\right)^{-1}\exp\left(\frac{4\gamma M_w}{\rho_wRTD_p}\right) \quad (6)$$

In Eq. (6), D_p (m) = particle diameter; t (s) = growth time; ρ_w (kg/m^3) = density of water; D (m^2/s) = air-water vapor diffusion coefficient at temperature T; M_w (18.0×10^{-3} kg/mol) = molecular weight of water; M_s = molecular weight of solute; m (kg) = mass of dissolved species; i = number of ions for the dissolved species; R(8.314 N m/mol K) = universal gas constant; P_∞ (Pa) = pressure of water vapor in mixed gas; T (K) and T_d (K) = mixed gas and particle surface temperature, respectively; Kn = Knudsen number; γ (N/m) = surface tension; and α (between 0 and 1) = accommodation coefficient.

The fourth-order Runge-Kutta method was used to calculate the particle growth equation, Eq. (5). After a time step, Δt, the particle grows from the diameter $D_{pi}(t)$ to $D_{pi}(t+\Delta t)$. The reduced mass of water vapor per unit gas volume after Δt is w_{loss} (kg/m^3), which equals the mass of water condensed on the particle surface per unit gas volume. The w_{loss} can be shown to be

$$w_{\text{loss}} = \sum_i Nf_i\frac{\pi}{6}\rho_w(D_{pi}^3(t+\Delta t) - D_{pi}^3(t)) \quad (7)$$

where f_i = fraction of particles with the diameter $D_{pi}(t)$; and N (particles/m^3) = total number concentration.

After Δt, the absolute humidity, $w_3(t)$, and temperature of the mixed gas, $T_3(t)$, are changed to $w_3(t+\Delta t)$ and $T_3(t+\Delta t)$ as

$$w_3(t+\Delta t) = \frac{M_{a3}w_3(t) - w_{\text{loss}}Q}{M_{a3}} = w_3(t) - \frac{w_{\text{loss}}Q}{M_{a3}} \quad (8)$$

$$T_3(t+\Delta t) = T_3(t) + \frac{w_{\text{loss}}Qh_{fg3}}{M_{a3}C_{pa} + M_{a3}w_3(t+\Delta t)C_{pg} + w_{\text{loss}}QC_{pw}} \quad (9)$$

where Q (m^3/s) = volumetric flow rate of mixed gas; and h_{fg3} (J/kg) = condensation latent heat of water vapor.

Particle Control Efficiency

In the literature, extensive research has been conducted on the control efficiency (or 1.0—penetration) and pressure drop of venturi scrubbers (Ekman and Johnstone 1951; Calvert 1970; Yung et al. 1978; Tigges and Mayinger 1984). In this study, the particle control efficiency of the venturi scrubber was determined using Calvert's (1970) and Yung's (1978) theory. According to Yung's theory (1978), the penetration of a particle with diameter D_p can be expressed as

$$\begin{aligned}\frac{\ln P}{B} = {} & \frac{1}{K_{p0}(1-u_{d1})+0.7}\Bigg[4K_{p0}(1-u_{d1})^{1.5} + 4.2(1-u_{d1})^{0.5} \\ & - 5.02K_{p0}^{0.5}\left(1-u_{d1}+\frac{0.7}{K_{p0}}\right)\tan^{-1}\left(\frac{(1-u_{d1})K_{p0}}{0.7}\right)^{0.5}\Bigg] \\ & - \frac{1}{K_{p0}+0.7}\Bigg[4K_{p0} + 4.2 - 5.02K_{p0}^{0.5}\left(1+\frac{0.7}{K_{p0}}\right) \\ & \times\tan^{-1}\left(\frac{K_{p0}}{0.7}\right)^{0.5}\Bigg]\end{aligned} \quad (10)$$

where

$$B = \frac{Q_l\rho_D}{Q_g\rho_aC_{D0}} \quad (11)$$

$$K_{p0} = \frac{\rho_pC_pD_p^2|v_p - v_D|}{9\mu_aD_L} \quad (12)$$

$$u_{d1} = 2[1 - x^2 + (x^4 - x^2)^{0.5}] \quad (13)$$

$$x = 1 + \frac{3LC_{D0}\rho_a}{16D_L\rho_D} \quad (14)$$

In Eqs. (10)–(14), Q_l and Q_g (m^3/s) = volumetric flow rate of liquid and gas, respectively; μ_a (N s/m^2) = dynamic viscosity of air; V_p and V_D(m/s) = velocity of particle and droplet at the venturi throat, respectively; K_{p0} = inertial parameter (dimensionless) at the throat entrance; C_p = slip correction factor; C_{D0} = drag coefficient (dimensionless) at the throat entrance; L = throat length (m); and ρ_D and ρ_p (kg/m^3) = density of droplets and particles, respectively. The Sauter mean diameter of droplets, D_L (m), can be derived from the equation of Boll et al. (1974) as

J. Environ. Eng. 2007.133:454-461.

$$D_L = \frac{4.22 \times 10^{-2} + 5.77 \times 10^{-3}\left(\frac{1{,}000 Q_l}{Q_g}\right)^{1.922}}{v_{\mathrm{rel}}^{1.602}} \tag{15}$$

where v_{rel} (m/s)=relative velocity of gas and liquid at the nozzle.

The penetration of the particle by the venturi scrubber expressed by Calvert's theory (1970) is

$$P = \exp\left[\frac{2}{55}\frac{Q_l}{Q_g}\frac{\rho_D D_L}{\mu_a} v_t F(K_{pt}, f)\right] \tag{16}$$

$$K_{pt} = \frac{\rho_p C_p D_p^2 v_t}{9\mu_a D_L} = \frac{2\mathrm{St}}{1 - u_t} \tag{17}$$

$$\mathrm{St} = \frac{\rho_p C_p D_p^2 (v_t - v_D)}{18\mu_a D_L} \tag{18}$$

$$F(K_{pt}, f) = \frac{1}{K_{pt}}\left[-0.7 - K_{pt} f + 1.4 \ln\left(\frac{K_{pt} f + 0.7}{0.7}\right) + \frac{0.49}{0.7 + K_{pt} f}\right] \tag{19}$$

where f=empirical factor; v_t (m/s)=velocity of gas at the venturi throat, respectively; K_{pt}=dimensionless parameter; St=Stokes number; and u_t=velocity ratio of droplet and gas at the throat.

Results and Discussions

Fine Particle Control Efficiency

NaCl and SiO_2 particles were tested in the laboratory for the control efficiency of the venturi scrubber system. At the inlet of the venturi scrubber, the total number concentration (TNC), number median diameter (NMD), and geometric standard deviation (GSD) were measured by the SMPS to be: TNC=7.58×10^6–1.03×10^7 #/cm^3, NMD=105–125 nm, GSD=2.03–2.19 for NaCl particles; and TNC=3.69×10^6–6.37×10^6 #/cm^3, NMD=142–159 nm, GSD=2.22–2.38 for SiO_2 particles at the gas flow rate of 200–300 L/min. These particle distributions were used in the subsequent theoretical calculations. Figs. 3(a–c) show the control efficiencies of NaCl particles at different liquid to gas ratios for the gas flow rate of 200, 250, and 300 L/min, respectively. It is clear from Figs. 3(a–c) that the particle control efficiency by the present venturi scrubber (with saturated stream at 100°C) is much greater than that of the traditional venturi scrubber (without saturated steam). The results indicate that adding saturated steam is effective to enhance the fine particle control efficiency due to nucleation and condensation growth. For example, the control efficiency of the present venturi scrubber system for NaCl particles greater than 100 nm is greater than 84, 95, and 94%, respectively, and it is only 22, 40, and 41% for the traditional venturi scrubber for the gas flow rate of 200, 250, and 300 L/min, respectively, when the liquid to gas ratio is 2.5 L/m^3. For both the present and traditional venturi scrubbers, the particle control efficiency increases as the liquid to gas ratio is increased.

Similar results can be seen for SiO_2 particles in Figs. 4(a–c). The particle control efficiency of the traditional venturi scrubber is found to be low, typically below 35, 47, and 58% at the liquid to gas ratio of 2.5 L/m^3 for the gas flow rate of 200, 250, and 300 L/min, respectively. For the present venturi scrubber, the control efficiency increases from about 21, 14, and 4% at dp=50 nm to 81, 72, and 68% at dp=100 nm monotonically, then the efficiency gradually increases to 90, 89, and 88% at dp=478 nm at the liquid to gas ratio of 2.5 L/m^3 for the gas flow rate of 200, 250, and 300 L/min, respectively. For NaCl and SiO_2 particles, the influence of the gas flow rate on the particle control efficiency of the present venturi scrubber system is not obvious as shown in Figs. 3 and 4.

Pressure Drop

Fig. 5 shows the relationship between pressure drop and gas flow rate at different liquid to gas ratios for the present venturi scrubbers (with saturated steam at 100°C) and the traditional venturi scrubbers (without saturated steam). The difference of pressure drop between the present and the traditional venturi scrubber system was found to be small. It is seen that as the gas flow rate is increased, pressure drop also increases. When the gas flow rate is 300 L/min, pressure drop is found to be 12±1.7, 38±2.2, 55±4.7, and 79±7.5 cmH_2O (or 1.18±0.17, 3.72±0.22, 5.39±0.46, and 7.74±0.74 kPa) for the liquid to gas ratio of 0, 1.5, 2.0, and 2.5 L/m^3, respectively. Compared to the traditional venturi scrubber, the present venturi scrubber can remove fine particles efficiently at a reasonably low pressure drop. For example, the results indicate that for the present venturi scrubber at the flow rate of 250 L/min and the liquid to gas ratio of 2.5 L/m^3, the pressure drop is only about 44 cmH_2O (4.3 kPa), and the control efficiency for 0.1–0.3 μm particles is as high as 90–95%. In comparison, Calvert (1977) found that a traditionally run system needed a pressure drop of 200 cmH_2O (or 19.6 kPa) to achieve 50% removal of 0.6 μm particles at a liquid to gas ratio of 2.5 L/m^3.

Particle Growth

The experimental data suggest that adding saturated steam at 100°C in front of the venturi scrubber is effective for removing fine particles. Theoretical calculation was conducted to show how the mixing process affects particle growth and the control efficiency of the scrubber. The calculation assumed that water vapor was condensed on particle surfaces only, and there was no water vapor loss on the wall. Fig. 6 shows the influence of mixing ratio on the initial mixed saturation ratio at different waste stream relative humidities (fixed waste stream temperature at 25°C). It is seen that at 100% relative humidity, the initial mixed saturation ratio increases with an increasing mixing ratio, reaches a maximum value, and then decreases. The maximum value of the initial mixed saturation ratio is 2.91 when the mixing ratio is 0.17. Fig. 6 also shows that the initial mixed saturation ratio decreases as the relative humidity of the waste stream is decreased. That is, it is important to humidity the waste stream before mixing with saturated steam. In order to achieve high control efficiency at a low pressure drop, the condensation growth process must be operated at a high initial mixed saturation ratio but the lowest mixing ratio possible. We chose the mixing ratio around 0.1 for the current scrubber test with normal temperature waste stream. The experiment was conducted using normal temperature waste stream at 25°C. If waste stream temperature is higher, theoretical calculation shows that the initial mixed saturation ratio will decrease at a fixed mixing ratio. It is because a larger difference in temperature between the waste stream and saturated steam at 100°C will increase the initial mixed saturation ratio of mixed gas.

During particle growth process, droplet temperature will decrease and gas temperature will increase. It is because condensa-

J. Environ. Eng. 2007.133:454-461.

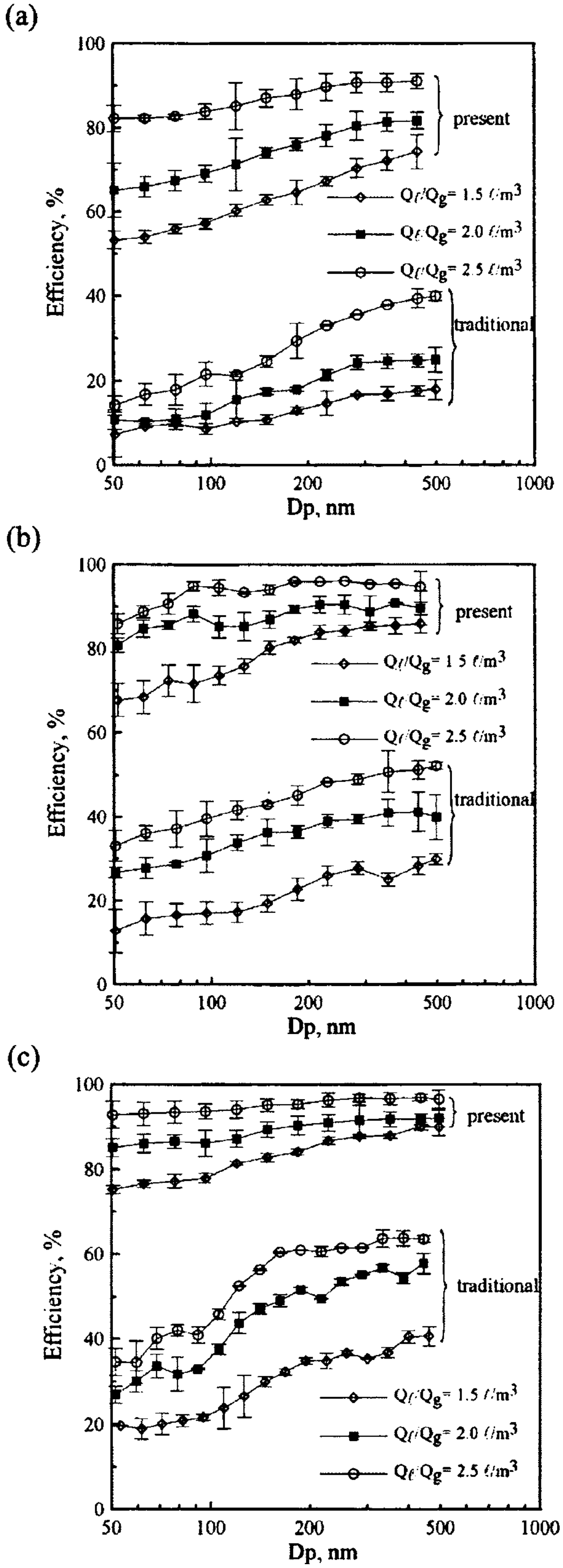

Fig. 3. The control efficiency for NaCl particle at different liquid to gas ratios for the gas flow rate of (a) 200 L/min; (b) 250 L/min; and (c) 300 L/min

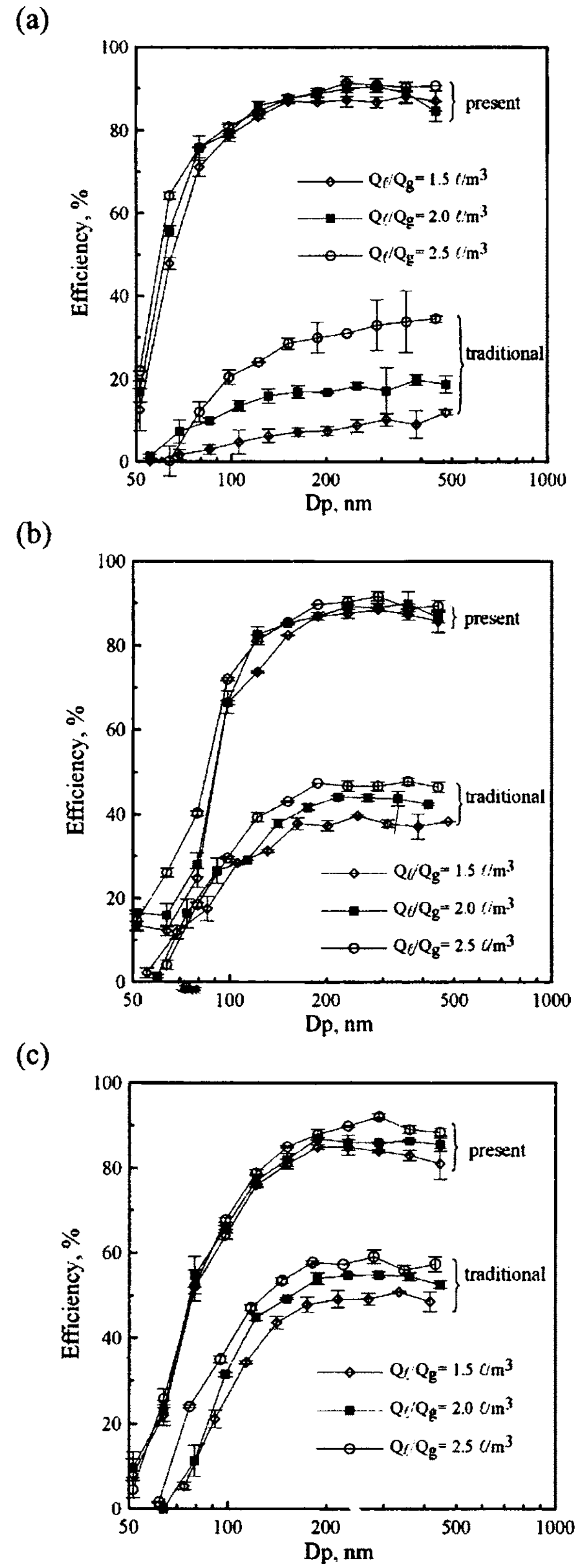

Fig. 4. The control efficiency for SiO_2 particle at different liquid to gas ratios for the gas flow rate of (a) 200 L/min; (b) 250 L/min; and (c) 300 L/min

J. Environ. Eng. 2007.133:454-461.

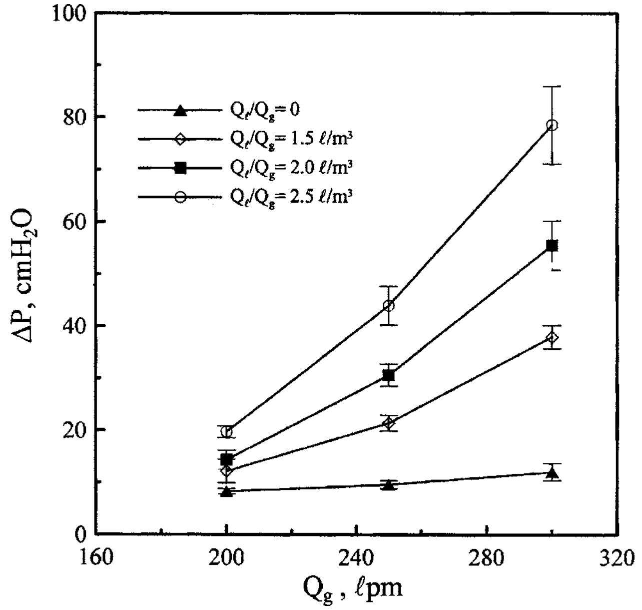

Fig. 5. The relationship between pressure drop and gas flow rate at different liquid to gas ratios (1 cmH_2O=98 Pa)

tion of water vapor on particles releases heat as particles grow. In addition, the saturation ratio will decrease with time as water vapor condenses on particles as shown in Fig. 7. These changes in temperature and saturation ratio has been taken into account in the theoretical calculations of particle growth. Fig. 8 shows the original distribution and calculated distribution of fine particles after the growth time of 4.0 ms for NaCl and SiO_2 particles for different accommodation coefficients. It is seen that the particles grow to a similar size distribution and the influence of accommodation coefficient is not important. Therefore, the accommodation coefficient was assumed to be 1.0 for the subsequent simulation.

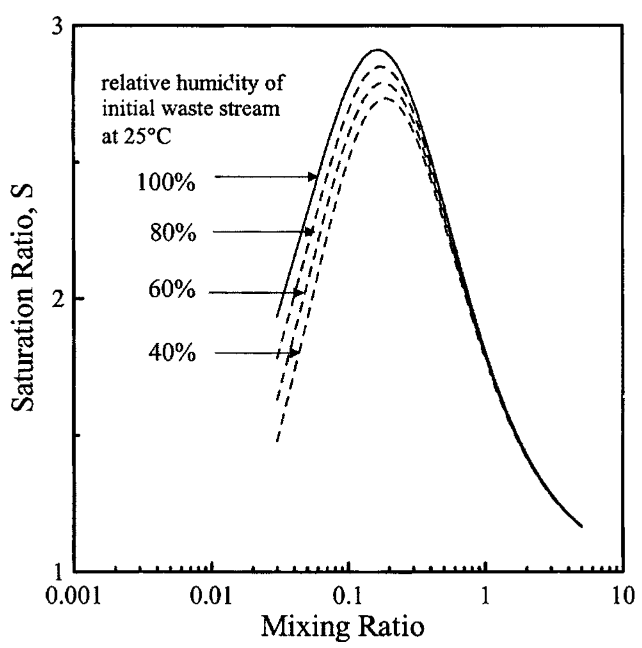

Fig. 6. The influence of mixing ratio on initial mixed saturation ratio at different relative humidities (when temperature is fixed at 25°C, saturated steam temperature=100°C)

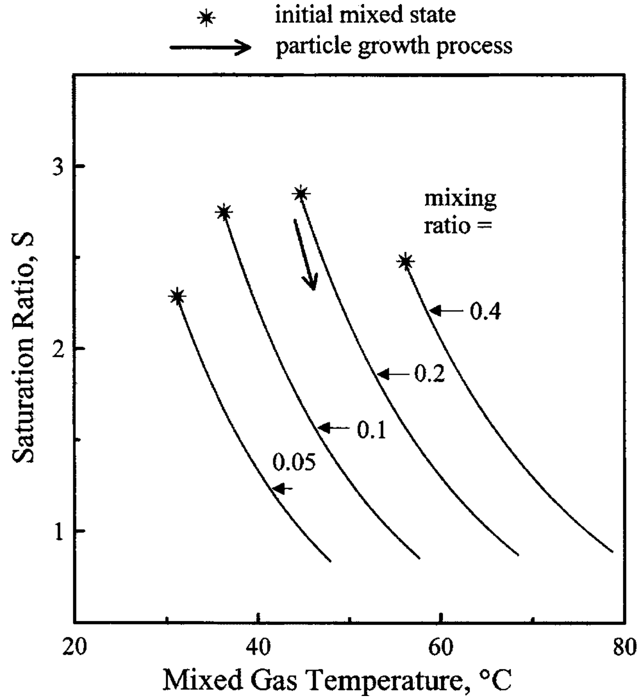

Fig. 7. The relationship of saturation ratio and mixed gas temperature at different mixing ratios (initial saturated steam temperature=100°C, waste stream temperature=25°C, RH=100%, accommodation coefficient=1, Q_g=300 L/min, TNC=8.72 $\times 10^6$ #/cm^3, NMD=118 nm, and GSD=2.08, NaCl particles)

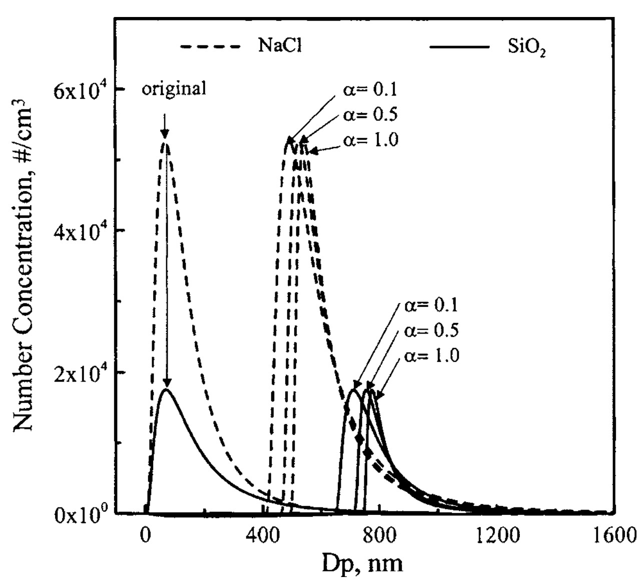

Fig. 8. The particle size distribution of NaCl and SiO_2 particles after condensation growth for different accommodation coefficients (initial saturated steam temperature=100°C, waste stream temperature=25°C, RH=100%, Q_g=300 L/min, original NaCl particles: TNC=8.72$\times 10^6$ #/cm^3, NMD=118 nm, GSD=2.08, mixing ratio=0.10, and original SiO_2 particles: TNC=3.69 $\times 10^6$ #/cm^3, NMD=142 nm, GSD=2.32, mixing ratio=0.097)

J. Environ. Eng. 2007.133:454-461.

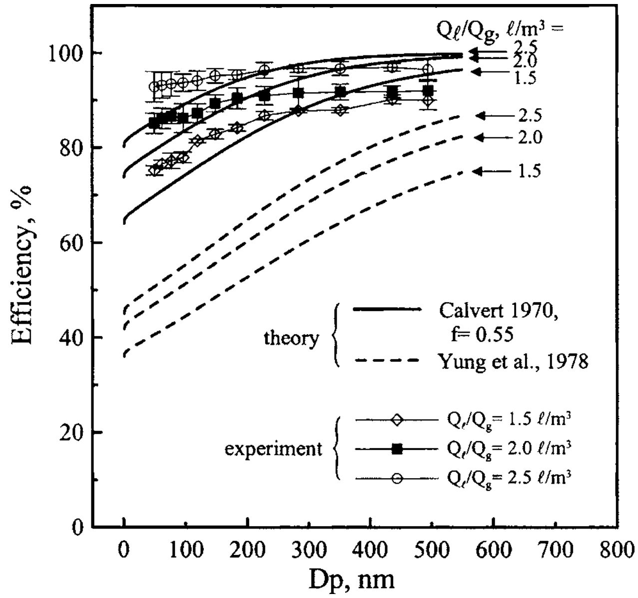

Fig. 9. Comparison of theoretical results of particle control efficiency with experimental data for NaCl particles

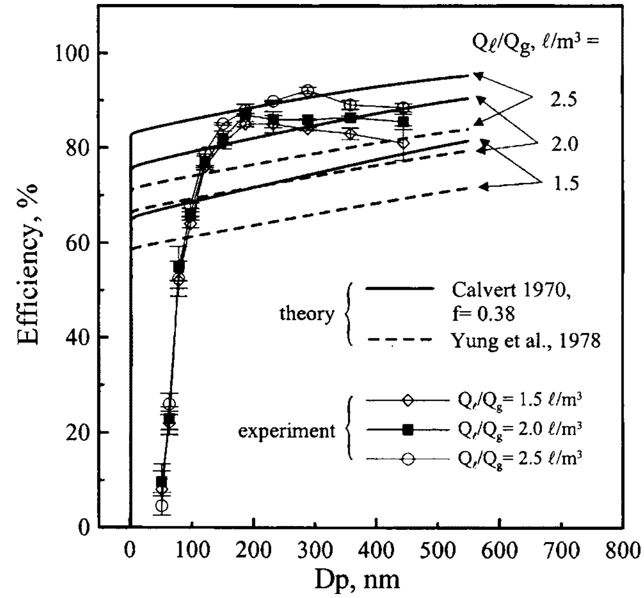

Fig. 10. Comparison of theoretical results of particle control efficiency with experimental data for SiO_2 particles

Fig. 8 also shows that the diameter of the grown SiO_2 particles is larger than NaCl particles. It is due to higher number concentration of NaCl particles which consumes more water vapor during particle growth than SiO_2 particles. As a result, the saturation ratio is lower and the final particle size is smaller.

Comparison of Theoretical Results with Experimental Data

Fig. 9 shows the comparison of the particle control efficiency between theoretical results and experimental data for NaCl particles by the present venturi scrubber when the gas flow rate is 300 L/min. The empirical factor, *f*, in Calvert's theory was assumed to be 0.55 for the best fit of the experimental data. It is seen that the theoretical efficiencies of Calvert's theory, which are greater than those of Yung's theory, agree well with the experimental data. The control efficiency remains higher than 75% for particles greater than 50 nm for all conditions. Below 50 nm, particle concentrations are not high enough to generate good experimental data although theory predicts a drop in the collection efficiency with decreasing particle size.

The comparison between theoretical results and experimental data of SiO_2 particles at the gas flow rate of 300 L/min is shown in Fig. 10. The empirical factor, *f*, in Calvert's theory was assumed to be 0.38 for hydrophobic SiO_2 particles for the best fit of the experimental data. It is seen that the theoretical control efficiencies for particles greater than 150 nm calculated by Calvert's theory are close to the experimental data, whereas deviations exist for particles less than 150 nm. Experimental data show that fine particle control efficiency is decreased sharply from about 80 to nearly 0% as particle size is decreased from 150 to 50 nm. Theory predicts a sharp drop in the control efficiency only when the particle size is close to 0 nm. Such deviation still remains to be resolved. For particles smaller than 150 nm, the control efficiency of SiO_2 particles is smaller than that of NaCl particles since the latter is hydrophilic (higher empirical factor *f*) while the former is hydrophobic (lower empirical *f*). The solute effect of NaCl particles also helps to reduce water vapor pressure at fine particle surface which increases growing particle size and control efficiency.

Figs. 9 and 10 show that Yung's theory predicts that the control efficiency of SiO_2 particles is higher than that of NaCl particles since the grown SiO_2 particle size is larger than NaCl particles as shown in Fig. 8. This is not consistent with the experimental collection efficiency data for particles smaller than 150 nm as shown in Figs. 9 and 10. Unlike Calvert's theory, Yung's theory does not contain the empirical factor *f* so that adjustment of the theoretical control efficiency based on particle's hydrophilic behavior is not possible. In Eq. (16), Calvert's theory suggested the empirical factor be 0.25 and 0.5 for hydrophobic and hydrophilic particles, respectively. In this study, we found that the factor is not the same for much smaller particle size range that we tested than that of Calvert's study. It is 0.38 and 0.55 for SiO_2 particles (hydrophobic) and NaCl particles (hydrophilic) for the best fit of the experimental data.

Conclusions

The operating pressure drop of the venturi scrubber is excessively high for removing submicron particles. This study has investigated the submicron particle control efficiency of a venturi scrubber system at the reasonable low pressure drop. The new venturi scrubber system makes use of saturated steam at 100°C to mix with normal temperature waste stream before the venturi scrubber. Experimental results show that the particle control efficiency by the present venturi scrubber is much greater than that of the traditional venturi scrubber whereas the pressure drop is much lower. It indicates that adding saturated steam is effective to enhance the submicron particle control efficiency due to nucleation and condensation growth. Theoretical calculation was also conducted to show the mixing process, particle growth, and the control efficiency of the present venturi scrubber. Theoretical particle control efficiency of the present venturi scrubber shows that Calvert's theory with a proper empirical factor *f* agrees with the

J. Environ. Eng. 2007.133:454-461.

experimental data for NaCl particles greater than 50 nm, and for SiO_2 particles greater than 150 nm.

Acknowledgments

The writers are thankful to the funding provided by the National Science Council, Taiwan, under Grant No. NSC 89-2211-E-009-064.

References

Boll, R. H. (1973). "Particle collection and pressure drop in venturi scrubbers." *Ind. Eng. Chem. Fundam.*, 12(1), 40–50.

Boll, R. H., Flais, L. R., Maurer, P. W., and Thompson, W. L. (1974). "Mean drop size in a full-scale venturi scrubber via transmissometer." *J. Air Pollut. Control Assoc.*, 24(5), 932–938.

Calvert, S. (1970). "Venturi and other atomizing scrubbers efficiency and pressure drop." *AIChE J.*, 16(3), 392–396.

Calvert, S. (1977). *Scrubbing in air pollution*, Academic, New York.

Chen, C. C., Shu, H. K., and Yang, Y. K. (1993). "Nucleation-assisted process for the removal of fine aerosol particles." *Ind. Eng. Chem. Res.*, 32(7), 1509–1519.

Chen, C. C., and Wu, M. C. (1992). "A nucleation process for the separation of fine particles from flue gas." *Chem. Eng. Sci.*, 47(7), 1581–1589.

Ekman, F. O., and Johnstone, H. F. (1951). "Collection of aerosols in a venturi scrubber." *Ind. Eng. Chem.*, 43(6), 1358–1363.

Fuchs, N. A., and Sutugin, A. G. (1971). *High dispersed aerosols, topics in current aerosol research (Part 2)*, Pergamon, New York.

Hayes, M., and Woods, K. (1996). "Treating semiconductor emissions with point-of-use abatement systems." *Solid State Technol.*, Oct., 141–148.

Tigges, K. D., and Mayinger, F. (1984). "Experiments with highly efficient venturi scrubbers for aerosol separation from gases under multi-plane water injection." *Chem. Eng. Process.*, 18(3), 171–179.

Tsai, C. J., Miao, C. C., and Lu, H. C. (1997). "White smoke emission from a semiconductor manufacturing plant." *Environ. Int.*, 23(4), 489–496.

Yoshida, T., Kousaka, Y., and Okuyama, K. (1976). "Growth of aerosol particles by condensation." *Ind. Eng. Chem. Fundam.*, 15(1), 37–41.

Yung, S. C., Calvert, S., Barbarika, H. F., and Sparks, L. E. (1978). "Venturi scrubber performance model." *Environ. Sci. Technol.*, 12(4), 456–459.

J. Environ. Eng. 2007.133:454-461.