Control Efficiency of Submicron Particles by an Efficient Venturi Scrubber System

Cheng-Hsiung Huang1; Chuen-Jinn Tsai2; and Yu-Min Wang3

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/m³, 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 cmH₂O (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 cmH₂O (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 SiO₂ particles greater than 150 nm.

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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 cmH₂O (or 19.6 kPa) when the liquid to gas ratio is 1.0 L/m³ (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 SiO₂ 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-
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/m³, 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 SiO₂ 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) can be expressed as follows:

$$\text{Mixing ratio} = \frac{\text{Mass flow rate of steam}}{\text{Mass flow rate of waste stream}}$$

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.

**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 steam, the mixing ratio (or the ratio of the steam to waste stream by mass flow rate) can be expressed as follows:
mixing ratio $= \frac{M_{w_2}}{M_{a_3}(1 + w_1)} \quad (1)$

where $M_{a_1}$ (kg/s) represents the mass flow rate of dry air in the waste stream; $M_{w_2}$ (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:

$$w_3 = \frac{M_{a_1}w_1 + M_{w_2}w_{1a} + M_{w_2}}{M_{a_3}^a + M_{a_3}^a} = M_{a_3}^a + M_{w_2} + M_{a_3}^a$$

$$w_{3a} = M_{a_3}^a + M_{a_3}^a + M_{a_3}^a$$

$w_{3a}$ (kg/s) and $M_{a_3}$ (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

$$T_3 = \frac{M_{a_1}(C_{p_a} + w_1C_{p_w})T_1 + M_{w_2}C_{p_w}T_2}{M_{a_3}(C_{p_a} + w_1C_{p_w}) + M_{w_2}C_{p_w}}$$

$C_{p_a}$ (1002.11 J/kg K) and $C_{p_w}$ (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:

$$S = \frac{w_3P_mV_g}{R_aT_3 + w_3P_mV_g} = \frac{w_3P_mV_g}{(R_a + w_3R_a)T_3}$$

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; $P_a$ (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

\[ dD_p \over dt = 4D_M \left( P_a \over T \right) \left( 0.75\alpha(1 + Kn) \over 0.75\alpha + 0.283 Kn \alpha + Kn^2 \right) \]

(5)

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

$$P_D = P_a \left[ 1 + 6\text{im} \over M_p \rho_p \pi D_p^2 \right]^{-1} \exp \left[ 4\gamma M_w \over \rho_p RTD_p \right]$$

(6)

In Eq. (6), $D_p$ (m) = particle diameter; $t$ (s) = growth time; $\rho_w$ (kg/m$^3$) = density of water; $D$ (m$^2$/s) = air-water vapor diffusion coefficient at temperature $T$; $M_w$ (18.07 x 10$^{-3}$ kg/mol) = molecular weight of water; $M_p$ = molecular weight of solute; $m$ (kg) = mass of dissolved species; $i$ = number of ions for the dissolved species; $R$(8.314 N m K/mol) = universal gas constant; $P_a$ (Pa) = pressure of water vapor in mixed gas; $T$ (K) and $T_g$ (K) = mixed gas and particle surface temperature, respectively; $Kn$ = Knudsen number; $\gamma$ (N/m) = surface tension; and $\alpha$ (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, $\Delta t$, the particle grows from the diameter $D_p(t)$ to $D_p(t + \Delta t)$. The reduced mass of water vapor per unit gas volume after $\Delta t$ 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

$$w_{loss} = \sum_i N_f \pi x_i^2 \left( D_p^2(t + \Delta t) - D_p^2(t) \right)$$

(7)

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

After $\Delta t$, 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

$$T_3(t + \Delta t) = T_3(t) + \frac{T_3w_3(t) - T_3w_3Q}{M_{a_3}} = T_3(t) - \frac{T_3w_3Q}{M_{a_3}}$$

(8)

$$T_3(t + \Delta t) = T_3(t) + \frac{w_{loss}Qh_{fg}}{M_{a_3}C_{pg} + M_{a_3}w_3(t + \Delta t)C_{pg} + w_{loss}QC_{pw}}$$

(9)

where $Q$ (m$^3$/s) = volumetric flow rate of mixed gas; and $h_{fg}$ (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 (Ekmann and Johnstone 1951; Calvert 1970; Young et al. 1978; Tiggles and Mayinger 1984). In this study, the particle control efficiency of the venturi scrubber was determined using Calvert’s (1970) and Young’s (1978) theory. According to Young’s theory (1978), the penetration of a particle with diameter $D_p$ can be expressed as

$$\ln P \over B = 1 \over K_{p0}(1 - u_d)^{1.5} + 4.2(1 - u_d)^{0.5}$$

$$- 5.02K_{p0}^{1.5} \over K_{p0} \left[ 1 - u_d + 0.7 \over K_{p0} \right] \tan^{-1} \left[ (1 - u_d)K_{p0} \over 0.7 \right]$$

$$- 1 \over K_{p0} + 0.7 \left[ 4K_{p0} + 4.2 - 5.02K_{p0}^{1.5} \over 1 + 0.7 \over K_{p0} \right] \tan^{-1} \left[ K_{p0} \over 0.7 \right]^{0.5}$$

(10)

where

$$B = QD_p \over QD_pC_{D0}$$

(11)

$$K_{p0} = \rho_p C_{Dp}D_p^2 \left[ \rho_p - \rho_d \right] \over 9 \mu_d D_L$$

(12)

$$u_d = 2 \left[ 1 - x^2 + (x^2 - x^2)^{0.5} \right]$$

(13)

$$x = 1 + 3LC_{D0} \rho_p \over 16D_L \rho_D$$

(14)

In Eqs. (10)–(14), $Q$, and $Q_{D0}$ (m$^3$/s) = volumetric flow rate of liquid and gas, respectively; $\mu_d$ (N·s/m$^2$) = dynamic viscosity of air; $V_p$ and $V_g$ (m/s) = velocity of particle and droplet at the venturi throat, respectively; $K_{p0}$ = inertial parameter (dimensionless) at the throat entrance; $C_{p0}$ = slip correction factor; $C_{D0}$ = drag coefficient (dimensionless) at the throat entrance; $L$ = throat length (m); and $g_D$ and $\rho_p$ (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...
The penetration of the particle by the venturi scrubber expressed by Calvert’s theory (1970) is

\[
P = \exp \left[ \frac{2Q_L}{55Q_g} \frac{Q_L}{Q_g} \frac{\mu_d}{\mu_a} f(K_{pt}, f) \right]
\]

(16)

\[
K_{pt} = \frac{\rho_L C_p D_p^2 v_f}{9 \mu_a D_L} = \frac{2St}{1 - u_t}
\]

(17)

\[
St = \frac{\rho_L C_p D_p^2 (v_f - v_d)}{18 \mu_a D_L}
\]

(18)

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

(19)

where \(f\) = empirical factor; \(v_f\) (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 SiO₂ 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 \times 10^6–1.03 \times 10^7 #/cm³, NMD=105–125 nm, GSD=2.03–2.19 for NaCl particles; and TNC=3.69 \times 10^6–6.37 \times 10^6 #/cm³, NMD=142–159 nm, GSD=2.22–2.38 for SiO₂ 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 steam 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 10 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/m³. 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 SiO₂ 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/m³ 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/m³ for the gas flow rate of 200, 250, and 300 L/min, respectively. For NaCl and SiO₂ 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 cmH₂O (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/m³, 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/m³, the pressure drop is only about 44 cmH₂O (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 cmH₂O (or 19.6 kPa) to achieve 50% removal of 0.6 μm particles at a liquid to gas ratio of 2.5 L/m³.

### 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-
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<sub>2</sub> 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.
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 have 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 SiO₂ 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. 5. The relationship between pressure drop and gas flow rate at different liquid to gas ratios (1 cmH₂O=98 Pa)

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, \( Q_g = 300 \text{ L/min} \), TNC=8.72 \( \times 10^6 \) #/cm³, NMD=118 nm, and GSD=2.08, NaCl particles)

Fig. 8. The particle size distribution of NaCl and SiO₂ particles after condensation growth for different accommodation coefficients (initial saturated steam temperature=100°C, waste stream temperature=25°C, RH=100%, \( Q_g = 300 \text{ L/min} \), original NaCl particles: TNC=8.72 \( \times 10^6 \) #/cm³, NMD=118 nm, GSD=2.08, mixing ratio=0.10, and original SiO₂ particles: TNC=3.69 \( \times 10^6 \) #/cm³, NMD=142 nm, GSD=2.32, mixing ratio=0.097)
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 efficiencies of 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 50 to 500 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
experimental data for NaCl particles greater than 50 nm, and for SiO₂ particles greater than 150 nm.

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