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High-efficiency wet electrocyclone for removing fine and nanosized particles

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ABSTRACT

This study designed and tested a wet electrocyclone with high efficiency for long-term operation. The inner diameter of the collection electrode is 25 cm, and the discharge electrodes consist of seven circular discs with zigzag-shaped edges for particle charging and removal. The tip of the circular saw-type discs is 20 μm in diameter and the tip to the inner wall (collection electrode) spacing is 4 cm. Cleaning water near the inter wall was used to keep the collection electrodes clean. Experimental results showed that the collection efficiency of the present wet electrocyclone decreased with an increasing air flow rate. The efficiency for oleic acid (OA) particles was reduced only slightly from 78–92% to 75–90% for particles from 22.1 to 805 nm in electrical mobility diameter (d_p) after 6 h of micro-Al_2O_3 loading test. In the field test, the collection efficiencies of the present wet electrocyclone for submicron SiO_2 particles with mass concentration of 20–50 mg/m^3 were also found to keep higher than 93% for continuous 14-day operation.

A modified Deutsch-Anderson model was developed to predict the charged particle collection efficiency ($\eta_{elec,p}$, %) of nanoparticle as well as larger particles. The present model is $\eta_{elec,p}$ (%) $= 1 - \exp\{-[A(N_{De}^B) + C(N_{De}) + D]\} \times 100\%$, where A, B, C and D are regression coefficients, and N_{De} is the modified Deutsch number. Good agreement was obtained between the present predictions and experimental data.

1. Introduction

A cyclone is a simple dust control device, which is cost efficient to construct, operate, and maintain [1,2]. It is capable of handling large flow rate with low pressure drop [3,4]. The cutoff aerodynamic diameter (d_{pa50}) of a cyclone is usually greater than 5–10 μm, and therefore it is used as a pre-collector in front of other high-efficiency devices [1], such as electrostatic precipitators (ESPs). By combining ESPs and cyclones, electrocyclones were developed to control fine particles efficiently without an increase in pressure drop and reduce capital costs [5]. The effect of various operation conditions on particle collection efficiency was investigated in several experimental [4–8] and mathematical studies [9–13] for particles larger than 0.5 μm in diameter. In electrocyclones, high voltage is applied to a discharge electrode or vortex finder [6,9,10] which is installed in the central axis of cyclones to generate corona ions and electrostatic force. When particles are introduced into electrocyclones, they are charged by diffusion and field charging mechanism and then driven to the collection wall by electrostatic force in conjunction with centrifugal force [11–14]. The collection mechanism is dominated by electrostatic force to enhance collection efficiency for fine particles when the electric migration velocity is larger than terminal velocity [7].

The particle collection efficiency of electrocyclones was found to increase with an increasing particle residence time [7], the applied voltage [4,5], dust loading [5], and the length of the wire and the collection electrode [4,8]. The collection efficiency for particles in the size range of 0.5–10 μm can reach up to 99% as shown in Lim et al. [4]. However, the experimental data of particle collection efficiencies in electrocyclone for particles smaller than 0.5 μm are still lacking, and the mathematical model is not available. Besides, the deposition of particles on the discharge electrodes and collection electrodes [15,16], back corona [17] and particle re-entrainment [18,19] occurring in traditional dry ESPs may reduce collection efficiency of electrocyclone for particles in all size ranges.

In order to solve the problems of traditional dry ESPs and cyclones as mentioned above, wet ESPs [16,20] and wetted wall cyclones [19] have been developed, in which a continuous cleaning water flow is supplied to prevent the deposition and accumulation of particles on the collection electrode surfaces and particle re-entrainment caused by rapping [21]. However, the performance of the wet ESP [16,20] for long-term operation needs to be further investigated. Besides, for particles with diameter smaller than 2.5 μm, the collection efficiency of the wetted wall cyclone was shown to be lower than 60% and needs to be improved.

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The objective of this study is to develop a wet electrocyclone to enhance the collection efficiency of fine and nanosized particles. Clean recirculating water flow was supplied continuously to clean the wall of the cyclone, which is the collection electrode. The optimal operating factors of the present wet electrocyclone including the air flow rate, the pressure drop, and the cleaning water flow rate were examined. The collection efficiency at initially clean and particle loading conditions was tested and compared with that of dry electrocyclone. Finally, a modified Deutsch–Anderson equation was developed to predict the collection efficiency for fine and nanosized particle and then validated by using experimental data obtained by this study.

2. Experimental methods

2.1. The present wet electrocyclone

The schematic diagram and dimensions of the present wet electrocyclone are shown in Fig. 1. The wet electrocyclone is made of stainless steel, in which the discharge electrodes consisting of seven circular saw-type discs (the tip is 20 μm in diameter) is installed in the central axis of the collection electrode to generate corona ions and electric field. The tip to collection electrode spacing (d_y) and tip to tip spacing (S) are 40 and 18 mm, respectively. Clean recirculating water at the flow rate of 21 L/min is supplied tangentially at four different positions on the wall to prevent the deposition and accumulation of particles on the collection electrode surface. In order to clean the discharge electrodes, two spray nozzles (BIM-K, Ikeuchi Taiwan Co., Ltd.) were installed at the inlet and top of the wet electrocyclone to generate fine water mist with the Sauter diameter of 15–50 μm at the hydraulic pressure of 30 psi. The direction of the mist jet generated by the spray nozzles at the inlet and the top of the wet electrocyclone is parallel and perpendicular to the aerosol flow, respectively. The water flow rate is 0.15 L/min and air pressure is 60 psi. Water mist was also used to enhance fine particle collection efficiency by means of Coulombic force between electrically charged droplets and particles [22]. The cleaning water and water mist were collected by a reservoir at the bottom of the wet electrocyclone and filtered by 5 μm filters (CT-G9, Chanson Water Ionizers USA, Inc.) for recirculation.

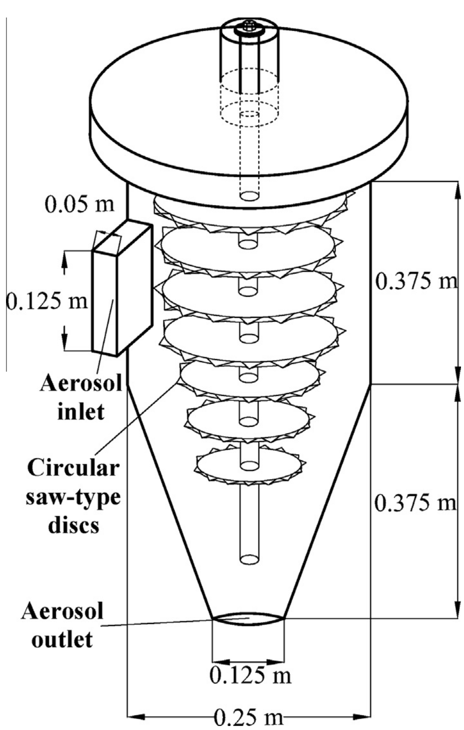

Fig. 1. Schematic diagram of the wet electrocyclone.

A blower was used to create the air flow rate of 1500–4500 L/min through the electrocyclone which was measured by a laminar flow meter (Model 50MC2-8, Meriam, USA). Generated test aerosols of less than 10 L/min were introduced into the electrocyclone after the laminar flow meter and dispersed by the incoming cleaning air. In this study, the particle collection efficiency experiment was conducted at the air flow rate (Q_a) of 1000, 2500, and 4500 L/min (corresponding to total particle residence time of 1.28, 0.50, and 0.28 s) when the present wet electrocyclone was initially clean under the following conditions: (1) high voltage was not applied, cleaning water and water mist were not supplied; (2) high voltage of 21 kV was applied, cleaning water and water mist were not supplied; (3) high voltage of 21 kV was applied, cleaning water and water mist were also supplied. Oleic acid particles (OA), and micro-Al_2O_3 (QF-Al-8000, Sipernat, Japan) were used as the test particles to investigate the effect of particle resistivity on collection efficiencies. The Polydisperse OA particles were generated by atomizing (Atomizer, TSI Model 3076) 8% (v/v) OA solution at 3 L/min, and then the aerosol flow was dried by a silica gel drier. Micro-Al_2O_3 was dispersed by a Jet-O-Mizer (Model 000, Fluid Energy Processing and Equipment Co., Hatfield, UK) at an air flow rate of 10 L/min corresponding to a mass loading rate of 10 g/h. All test particles were diluted by zero air in a mixing tank and then introduced into the wet electrocyclone. The particle generation system is shown in Fig. 2.

Fig. 3 shows the experimental setup for particle collection efficiency, particle loading test and field test. To generate an electric field and corona ions, high negative voltage was supplied to the discharge electrodes by using a high voltage D.C. power supplier (maximum output: 21 kV, 150 mA, Luxe Electric Co., Ltd., Taiwan). The voltage and corresponding corona current were measured by using a high voltage probe (HVP 40, Pintek Electronics Co., Ltd.) and a multi-meter (KT 325 DDM, Klter Electronicd institute Co., Ltd.). A scanning mobility particle sizer (SMPS, model 3085, TSI Inc.) with a condensation particle counter (CPC, model 3022, TSI Inc.) (range: 2.5–1000 nm) was used to measure the size distribution of the polydisperse OA based on electrical mobility diameter (d_p). A micro-orifice uniform deposit impactor (MOUDI, MSP Corp., Shoreview, MN, USA) was used to measure mass distribution based on aerodynamic diameter (d_{pa}) for micro-Al_2O_3. The characteristics and number size distribution of the test aerosols are shown in Table 1. The particle collection efficiency of the wet electrocyclone, $\eta_{total}(d_p)$, was calculated based on the number concentration (#/cm^3) of OA and the mass concentration of micro-Al_2O_3 (μg/m^3) by the following equation:

$$\eta_{total}(d_p)(\%) = \left(1 - \frac{C_{in}(d_p) - C_{out}(d_p)}{C_{in}(d_p)}\right) \times 100\% \quad (1)$$

where $C_{in}(d_p)$ is the particle inlet concentration and $C_{out}(d_p)$ is the outlet concentration for particles with d_p.

The particle loading effect on the collection efficiency of the wet electrocyclone was investigated based on the method described in Lin et al. [16]. The Jet-O-Mizer was used to disperse micro-Al_2O_3 at an aerosol flow rate of 10.0 L/min corresponding to the mass loading rate of 106.0 g/h. The amount of the particles penetration (W_{out}, g) was measured by the MOUDI at the outlet of the wet electrocyclone. After particle loading for 6 h, the quantity of particles on the collection electrode surface, W_{loaded} (g), was calculated to be 635.9 g by the following equation:

$$W_{loaded} = W_{total} - W_{outlet} \quad (2)$$

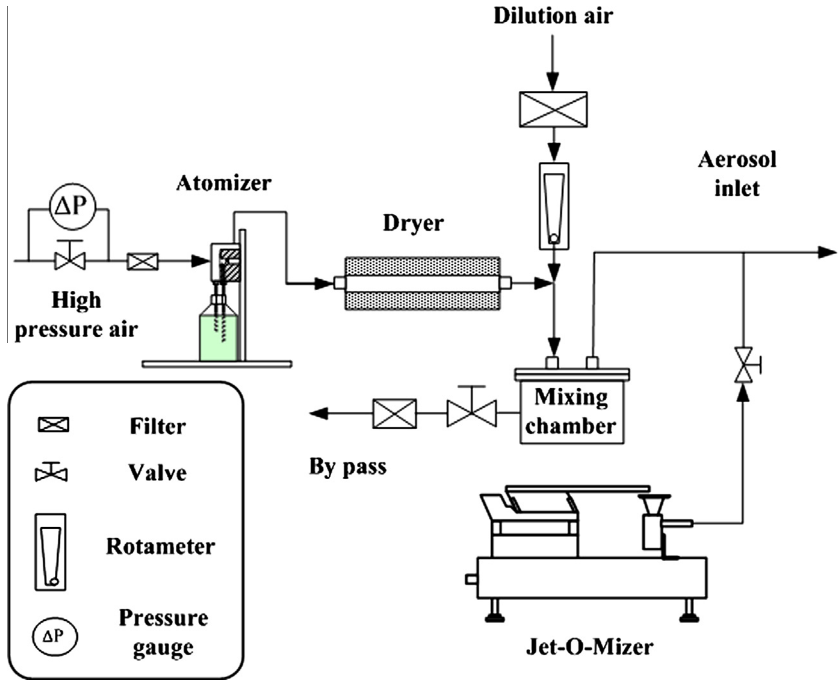

Fig. 2. Test particle generation system.

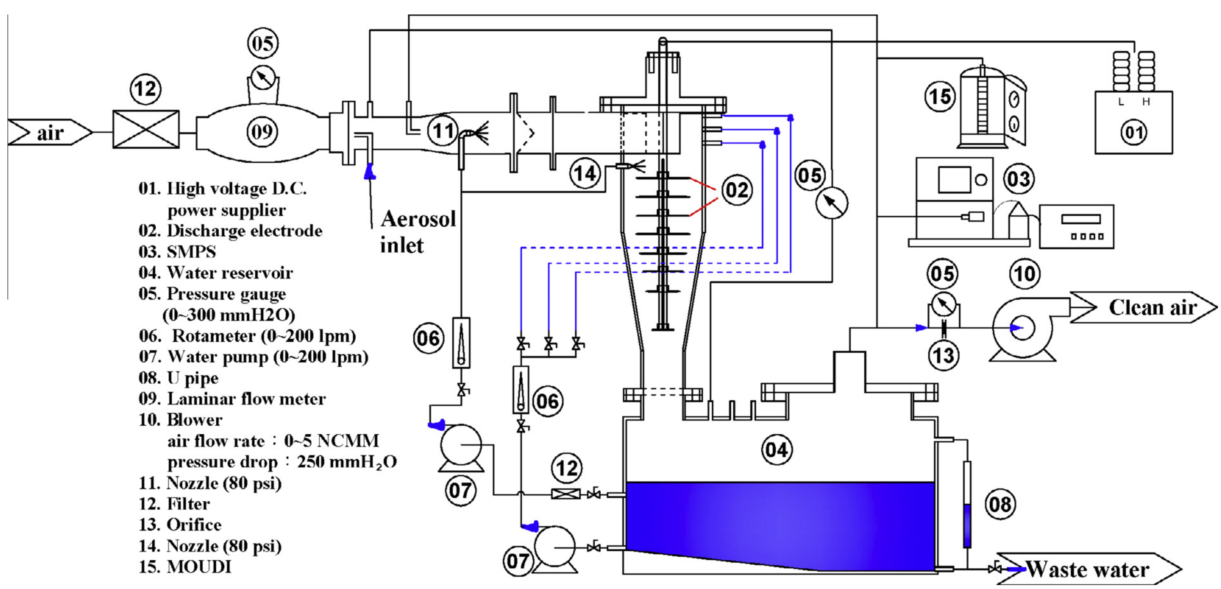

Fig. 3. Experimental setup for particle collection efficiency and particle loading tests.

Table 1
Characteristics of test particles.

	Size range	Apparent density	CMD (MMAD)	GSD	Resistivity (Ω-cm)	Total concentration
OA	22.1–805.8 nm		113.7 nm	1.96	2×10^6	4.67×10^5 (#/cm^3)
Micro-Al_2O_3	0.42–18.0 μm	0.267[a] (g/cm^3)	10.2 μm (MMAD)	2.38	>10^{14} [23]	154 (mg/m^3) (1000 L/min) 34.4 (mg/m^3) (2500 L/min) 15.2 (mg/m^3) (4500 L/min)
SiO_2	0.42–18.0 μm	0.04[b] (g/cm^3)	221 nm (MMAD)	2.15	10^{16} (bulk, [24])	20–50 (mg/m^3)

[a] Determined in this study according to CEN 15051 [37].
[b] From Tsai et al. [36].

where W_{total} (g) is the total particle dispersed by the Jet-O-Mizer. OA particles and micro-Al_2O_3 were used to examine the collection efficiency of the present wet electrocyclone respectively for nano-sized particles and particles with $0.4 \leqslant d_p \leqslant 20$ μm after 3–6 h of heavy particle loading. It is noted that OA particles were used for examining nanoparticle collection efficiencies instead of micro-Al_2O_3 because very few particles with $d_p \leqslant 100$ nm were generated by standard dispersive technique as found in Tsai et al. [25].

The field test was conducted continuously for 14 days to investigate the performance of the present wet electrocyclone during long-term operation in an exhaust stack of an optoelectronic company in Linkou, Taiwan, where fine SiO_2 particles were emitted. The MOUDI and filter samplers were used to measure the mass distributions and total mass concentrations of particulate matters in the exhaust gas, respectively.

3. Theoretical model

3.1. Electric field and ion current

Fig. 4 shows the schematic diagram of a typical multiple needle-to-plate electrostatic precipitator. The ion current, I_t, is calculated as follows [26,27]:

$$I_t = N \times I \tag{3}$$

$$I = \alpha_i \varepsilon_0 Z_i V_a (V_a - V_0)/d_y \tag{4}$$

where N is the number of tips in the wet electrocyclone, I is the ion current for single needle, α_i is the empirical coefficient, which is shown in Eq. (8), ε_0 is the gas permittivity (C^2/N m^2), Z_i is the ion mobility (m^2/V s), V_a is the applied voltage (V), V_0 is the breakdown voltage (V), which is calculated as [27,28]:

$$V_0 = \frac{E_s \cdot r \cdot \ln\left(\frac{4d_y}{r}\right)}{2} \tag{5}$$

where

$$E_s = 3.1 \times 10^4 \delta \left(1 + \frac{0.308}{\sqrt{0.5r\delta}}\right) \tag{6}$$

$$\delta = \frac{T_0 P}{T P_0} \tag{7}$$

In the above equations, E_s is the breakdown electric filed (V/m), P is the air pressure (bar), P_0 is the standard pressure (bar), T is the air temperature (°K), T_0 is the standard temperature (°K), and r is the radius of the tip of discharge electrode (m). To calculate α_i, the following equation is used:

$$\alpha_i = f(S/d_y) = E \cdot \left(\frac{S}{d_y}\right)^F \tag{8}$$

where E and F are regression coefficients, which are calculated to be 1.16 and 0.55, respectively, by fitting Eq. (8) to the experimental data of El-Mohandes et al. [29]. α_i was calculated to be 0.75 with corresponding d_y of 40 and S of 18 mm in the present wet electrocyclone. However, when α_i of 0.75 was used, a large deviation in the V–I curve between predicted values and experimental data was obtained. When α_i value of 2.1 was used, which is the maximum value proposed by Sigmond [30] for the multi-needle electrode, good agreement was obtained. This result will be shown and discussed later. After obtaining α_i, the current density on the plate, $J(\theta)$, is calculated by using Warburg formula as [30]:

$$J(\theta) = J(0)\cos^m \theta, \quad \theta \leqslant 63^\circ \tag{9}$$

$$J(0) = \frac{\varepsilon_0 \cdot Z_i \cdot V_a(V_a - V_0)}{d_y^3} \tag{10}$$

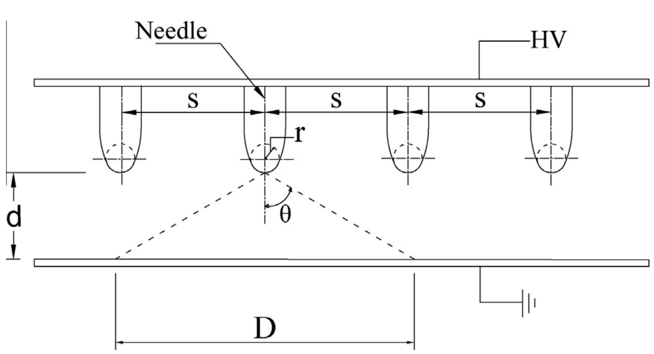

Fig. 4. Schematic diagram of a typical multiple needle-to-plate electrostatic precipitator.

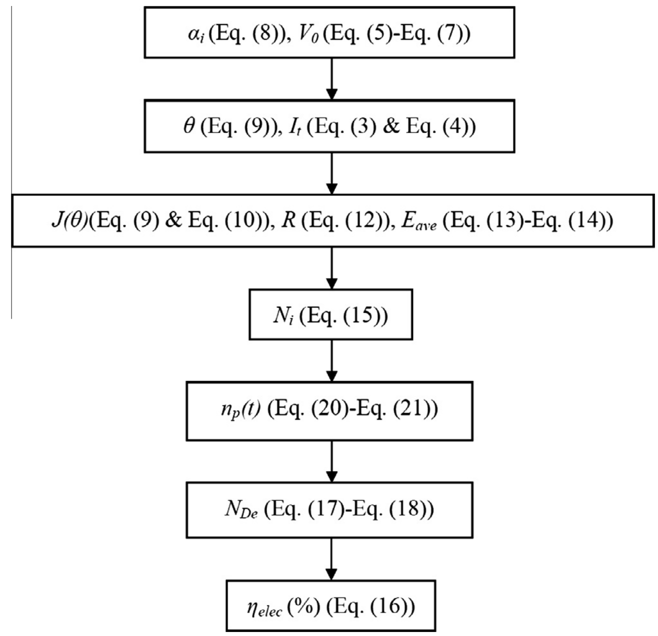

Fig. 5. Flow chart for the calculation procedure of particle collection efficiency in the wet electrocyclone.

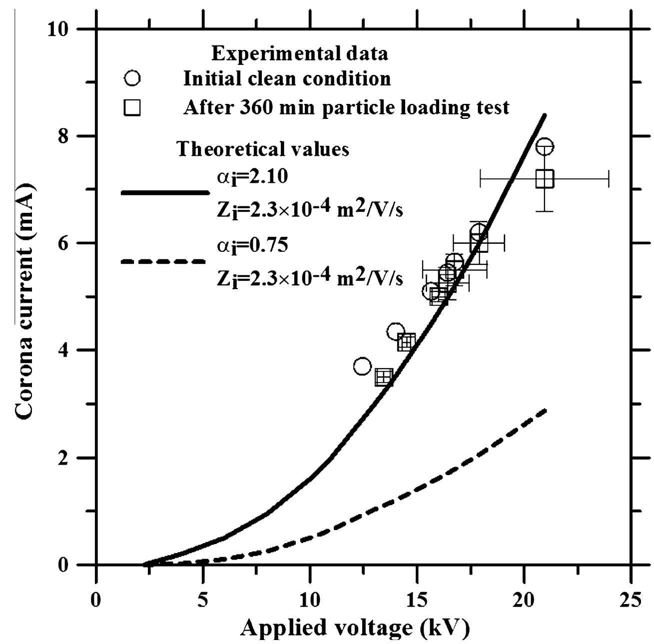

Fig. 6. Comparison of V–I curve between the theoretical values and the experimental data in the wet electrocyclone.

$$\alpha_i = \frac{2\pi}{m-2} \cdot \left\{1 - [1 + (\tan\theta)^2]^{\left(1-\frac{m}{2}\right)}\right\} \tag{11}$$

$$R = d_y \cdot \tan(\theta) \tag{12}$$

where m is 4.82 and 4.65 for positive and negative corona, respectively, θ is the subtending half-apex angle for the triangle of the distribution of corona from a tip of electrode over the collection electrode surface, and R is the radius of drift region on the collection electrode surface (m).

The vertical electric field distribution from the tip to the collection electrode ($E_{ave,}$ V/cm), $E_y(y)$, is given by [31]:

$$E_y(y) = \frac{2V_a}{\ln\left(\frac{4d_y}{r}\right)} \frac{1}{2y + r - \frac{y^2}{d_y}} \tag{13}$$

where y is the distance from the tip of the discharge electrode (m). The electric field strength at x direction, E_x, is assumed to be zero. Therefore, the average electric field strength, E_{ave}, is given by:

$$E_{ave} = \frac{\int_0^{d_y} E_y(y)dy}{d_y} \tag{14}$$

After $J(\theta)$, E_{ave} are obtained, the average ion concentration (N_i, #/m^3) is calculated as:

$$N_i = \frac{J(\theta)}{Z_i E_{ave} e} \tag{15}$$

3.2. Particle collection efficiency

The following semi-empirical equation is developed based on the method in Lin et al. [32] to calculate the charged particle collection efficiencies of wet electrocyclones ($\eta_{elec,p}(d_p)$):

$$\eta_{elec,p}(\%) = 1 - \exp\{-[A(N_{De}^B) + C(N_{De}) + D]\} \times 100\% \tag{16}$$

where A, B, C, and D are regression coefficients obtained by fitting Eq. (14) to the experimental data of the present study, N_{De} is the modified Deutsch number which is defined as:

$$N_{De} = \frac{W \cdot A}{Q} \tag{17}$$

in which A is the area of the collection electrode surface (m^2), Q is the air flow rate (m^3/s), and W is the particle migration velocity(m/s), which is calculated by:

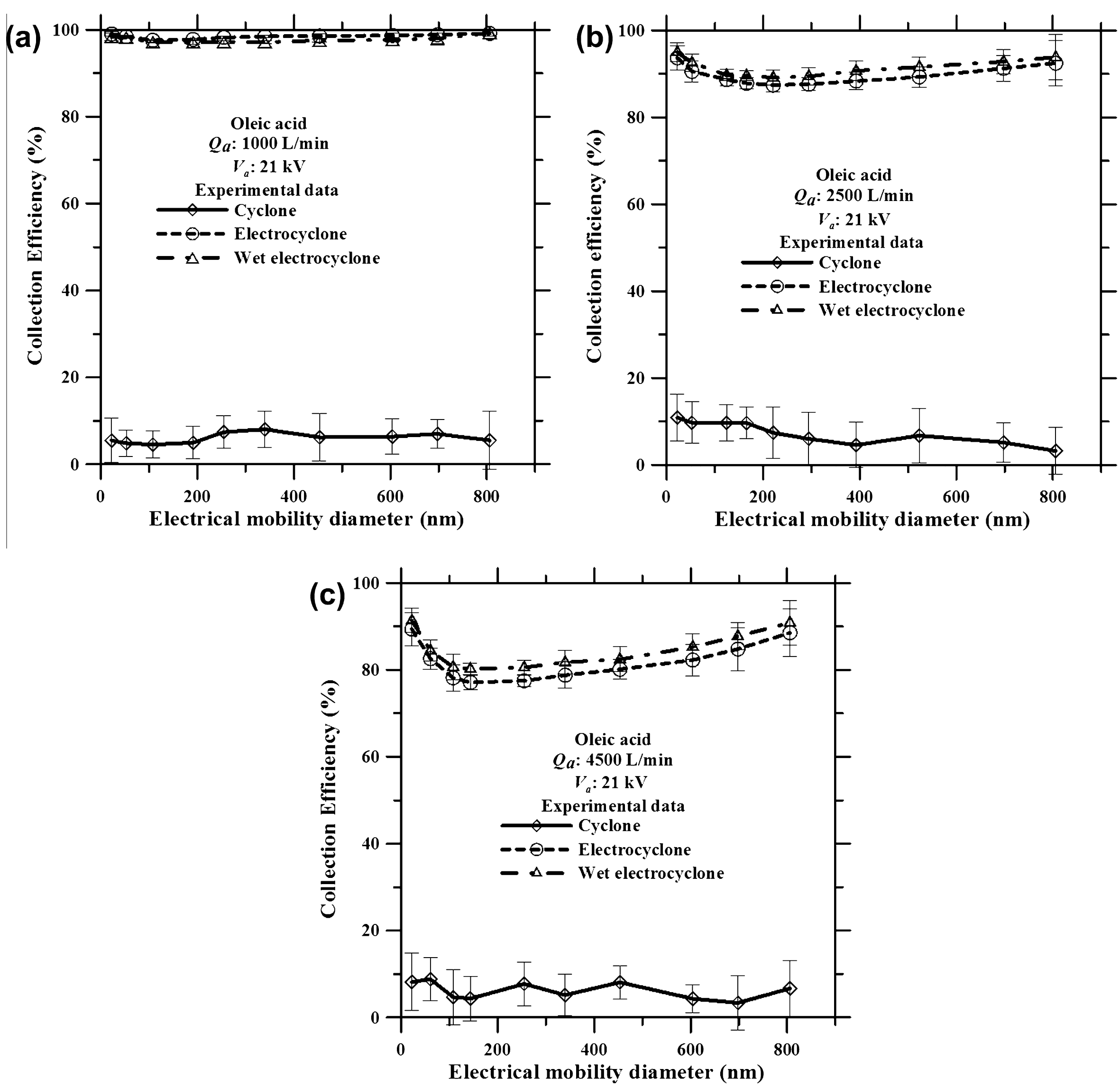

Fig. 7. Collection efficiency of the present wet electrocyclone under three operation conditions at the aerosol flow rate of 1000–4500 L/min and applied voltage of 21 kV.

$$W = \frac{n_p(t) E_{\text{ave}} C(d_p)}{3\pi\mu d_p} \tag{18}$$

where $C(d_p)$ is the slip correction factor of particles with d_p (μm), μ is the air viscosity (N-s/m^2), $n_p(t)$ is the total number of elemental units of particle charges as function of time, which is given by [32]:

$$n_p(t) = n_{diff}(t) \times \exp[a \times n_{diff}(t)^b + c n_{diff}(t) + d] + n_{field}(t) \tag{19}$$

where

$$n_{diff}(t) = \frac{d_p kT}{2K_E e^2} \ln\left(1 + \frac{\pi K_E d_p \bar{c}_i e^2 N_i t}{2kT}\right) \tag{20}$$

$$n_{field}(t) = \left(\frac{3\varepsilon}{\varepsilon + 2}\right)\left(\frac{E_{ave} d_p^2}{2K_E e}\right)\left(\frac{\pi K_E e Z_i N_i t}{1 + \pi K_E e Z_i N_i t}\right) \tag{21}$$

In the above equations, a is 1.91588, b is -0.1425, c is 1.296×10^{-5}, and d is -1.2671, $\bar{c}_t$ is the mean thermal speed of ion (m/s), ε is the relative permittivity of particle, k is the Boltzmann constant (1.38×10^{-23} J/K), $K_E = 9.0 \times 10^9$ (N-m/C^2), e is the elementary charge (C), N_i is the ion concentration (#/m^3), t is the residence time of particles in the charged region of wet electrocyclones (s), which is given by:

$$t_e = V_{\text{cyclone},cr} - V_{\text{outlet},cr} \tag{22}$$

where $V_{\text{cyclone,cr}}$ is the volume of cyclone in the particle charged region (m^3), which depends on R, $V_{\text{outlet,cr}}$ is the volume of cyclone outlet in the particle charged region (m^3).

3.3. Calculation procedure

Fig. 5 shows the calculation procedure for the average electric field and ion concentration, particle charging, and particle collection in the present model. α_i and V_0 are first calculated by using Eq. (8) and Eqs. (5)–(7), respectively. After obtaining α_i, θ and I_t are calculated by Eq. (11) and Eqs. (3) and (4), respectively. The current density on the plate ($J(\theta)$), the radius of drift region on the collection electrode surface (R), and the average electric field (E_{ave}) then can be calculated by Eqs. (9), (10), (12), (13), (14), respectively. Finally, N_i and $n'_p(t)$ are obtained by Eqs. (15), (20), and (21), respectively.

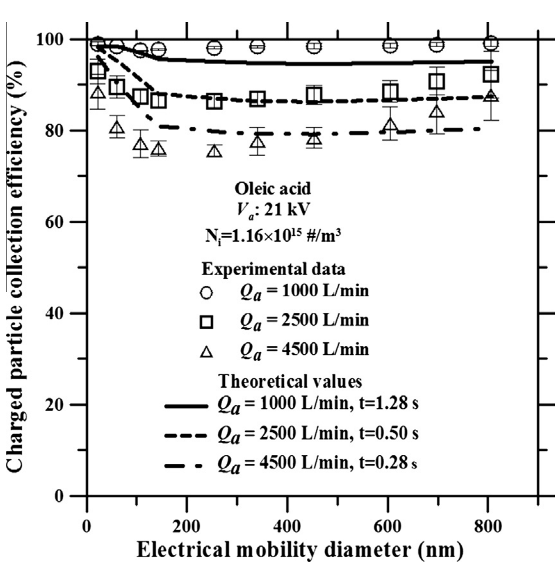

Fig. 8. Comparison of particle collection efficiency in the wet electrocyclone for OA particles between the present predictions and the experimental data at the aerosol flow rate of 1000–4500 L/min and the applied voltage of 21 kV.

After obtaining the average electric field, ion concentration and particle charge, particle collection efficiency in ESPs is calculated by using Eq. (16) with regression coefficients A, B, C, and D, which are obtained by fitting Eq. (16) to the experimental data obtained by the present study.

4. Results and discussion

4.1. Characteristics of the V–I curve

Fig. 6 shows the comparison of V–I curve between the theoretical values and the experimental data in the wet electrocyclone. Under the initially clean condition, the experimental results for ion current was measured to be 3.7–7.8 mA when the applied voltage was 12.5–21 kV with the critical voltage of 2.26 kV. In the V–I curve, large deviation between predicted values calculated by using α_i of 0.75 and experimental data was obtained. It is because the shape of the discharge electrode in the wet electrocyclone is

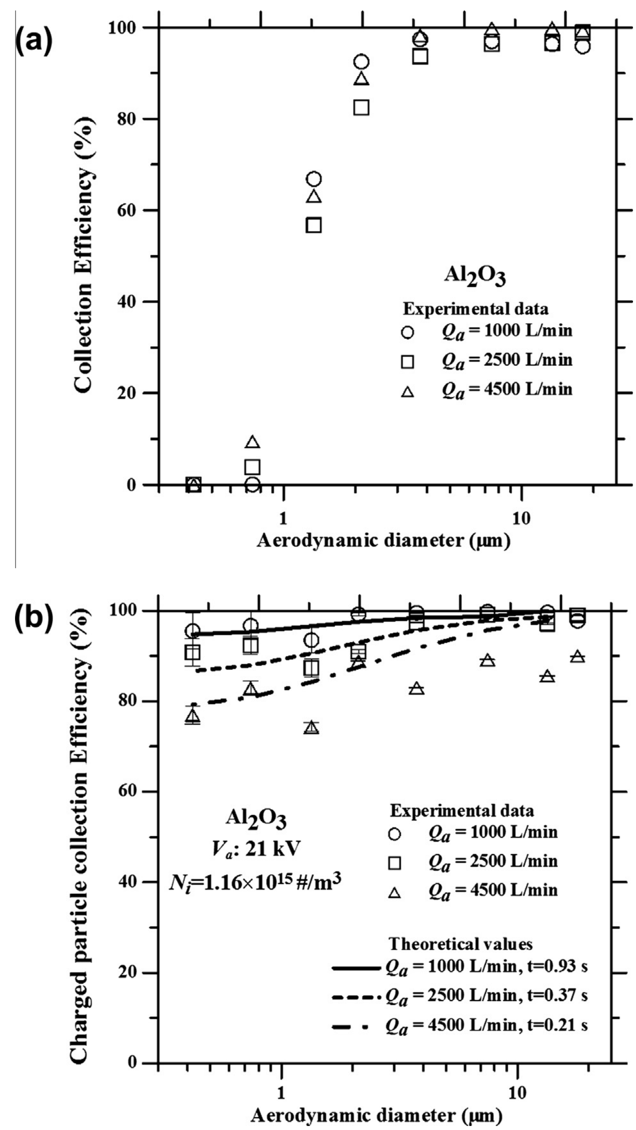

Fig. 9. Collection efficiency for micro-Al_2O_3. (a) Collection efficiency of the wet electrocyclone under condition 1. (b) Comparison of particle collection efficiency in the wet electrocyclone for micro-Al_2O_3 between the present predictions and the experimental data at the aerosol flow rate of 1000–4500 L/min and the applied voltage of 21 kV.

different from that in El-Mohandes et al. [29]. The tip of needles in EL-Mohandes et al. [29] is much sharper than the tip of the discharge electrode in the present wet electrocyclone. Therefore, Eq. (8) is not applicable to calculate α_i in the wet electrocyclone. Instead, it was found that when α_i of 2.1 and the ion mobility of 2.3×10^{-4} m^2/V/s for negative ions [27] were used, good agreement between the calculated results and experimental data for the V–I curve was obtained. Thus, a fixed value of α_i of 2.1 was used to predict the ion current in the present wet electrocyclone. After 6 h of particle loading test in the dry electrocyclone, ion currents decreased from 3.7 to 3.5 mA and from 7.8 to 7.2 when the applied voltage were 12.5 and 21.0 kV, respectively. It was because the resistivity of dust layer accumulated on the collection electrode surface reduced electric field strength, and thus the particle collection efficiency was reduced. This will be discussed further in the later section.

4.2. Comparing the particle collection efficiency in the present wet electrocyclone

Fig. 7 shows the collection efficiency of the wet electrocyclone as a function of OA particles with $22.1 \leqslant d_p \leqslant 805.8$ nm when the aerosol flow rate is in the range of 1000–4500 L/min under three different conditions as mentioned in experimental method section. Under condition 1 (no high voltage, no cleaning water and water mist), the collection efficiencies for particles are shown to be lower than 10%. It is because centrifugal force is not high enough to remove submicron particles efficiently. The collection efficiencies are highly enhanced to 97.1–99.3% at 1000 L/min, 87.4–93.7% at 2500 L/min, and 80.2–91.3% at 4500 L/min under condition 2 (with high voltage of 21 kV, no cleaning water and water mist), and 97.1–99.3% at 1000 L/min, 89.1–94.9% at 2500 L/min, and 80.2–91.3% at 4500 L/min under condition 3 (with high voltage of 21 kV, cleaning water and water mist) due to high electrostatic precipitation efficiency. As shown in Fig. 7, the collection efficiencies decrease with the increasing aerosol flow rate from 1000 to 4500 L/min due to a decrease in particle retention time from 0.93 to 0.21 s in the wet electrocyclone, resulting in a decrease in the number of particle charge from 1.2–69.5 to 0.92–58.8.

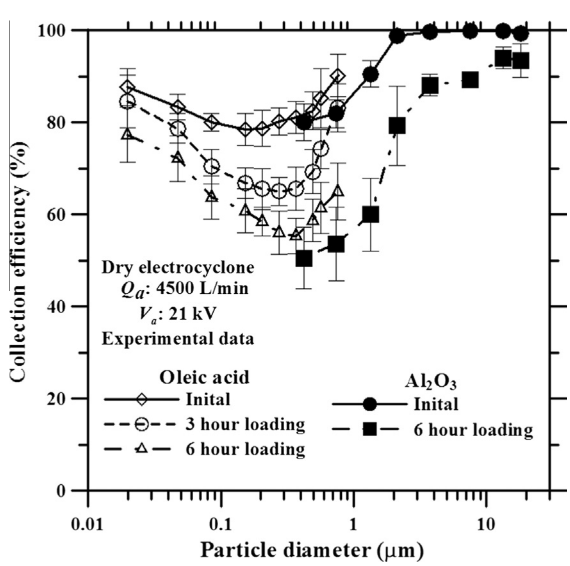

Fig. 10. Collection efficiency for OA particles and micro-Al_2O_3 in the dry electrocyclone at different TiO_2 loadings (Open symbols: electrical mobility diameter; closed symbols: aerodynamic diameter). The applied voltage and aerosol flow rate are 21 kV and 4500 L/min, respectively.

The present model is mainly used to predict collection efficiencies for charged particles removed by electrostatic forces in wet electrocyclones. In order to compare the present predictions with the experimental data, the experimental results of charged particle collection efficiencies, $\eta_{elec,e}(d_p)$, can be calculated by the following equations [16]:

$$\eta_{elec,e}(d_p)(\%) = \frac{\eta_{total}(d_p)(\%) - \eta_{cyclone}(d_p)(\%)}{100\% - \eta_{cyclone}(d_p)(\%)} \times 100\% \quad (23)$$

where $\eta_{cyclone}(d_p)$ (%) is the particle collection efficiencies of cyclones. The charged particle collection efficiencies were calculated to be 97.5–99.1% at 1000 L/min, 86.4–92.9% at 2500 L/min, and 75.6–88.4% at 4500 L/min. After obtaining the experimental results of charged particle collection efficiencies, the regression coefficients of 6.122 for A, 0.729 for B, −3.273 for C, and 0.582 for D are derived by fitting Eq. (16) to the experimental data for OA particles with $22.1 \leqslant d_p \leqslant 805.8$ nm when N_{De} is in the range from 0.1 to 4.0. The deviation between fitted curves and experimental data, as shown in Fig. 8, is 0.09–3.73%, 0.45–5.62%, and 0.54–9.33% at the aerosol flow rate of 1000, 2500 and 4500 L/min, respectively.

Fig. 9 shows the particle collection efficiency of the wet electrocyclone for micro-Al_2O_3 with $0.42 \leqslant d_{pa} \leqslant 18.0$ μm. Under condition 1, the collection efficiencies are 0–97.4% at 1000 L/min, 0–98.9% at 2500 L/min, and 0–99.3% at 4500 L/min, as shown in Fig. 9a. Under condition 3, the experimental results of charged particle collection efficiencies are calculated to be 95.5–99.9% at 1000 L/min, 86.7–98.7% at 2500 L/min, and 79.3–97.8% at 4500 L/min by using Eq. (22). The comparison of particle collection efficiencies between the present predictions and experimental data shows good agreement with deviation of 0.70–2.37% at 1000 L/min, 0.90–4.86% at 2500 L/min, and 1.21–10.3% at 4500 L/min, as shown in Fig. 9b.

4.3. Particle loading test and field test

The collection efficiency was tested under conditions 2 and 3 with an aerosol flow rate of 4500 L/min, an applied voltage of 21 kV, and with the micro-Al_2O_3 loading quantity of 106.0 g/h. The thickness of dust layer was measured to be 0.5 cm. As shown in Fig. 10, collection efficiencies for OA particles with $19.9 \leqslant d_p \leqslant 758.6$ nm decrease from 78.5–90.2% to 65.0–84.6% in the dry electrocyclone after 3 h of particle loading, and further decrease to 55.3–77.3% after 6 h of particle loading. For particles with $0.42 \leqslant d_{pa} \leqslant 18.0$ μm, collection efficiencies also decrease from 80.0–99.3% to 50.0–94.5%. Craters were observed on 10% area of dust layers due to the occurrence of back corona [15]. It is noted that a decrease in collection efficiencies for submicron particles is larger than that for micron particles because the electric field strength dominates the submicron particle collection efficiencies which are decreased due to the accumulation of micro-Al_2O_3 on the collected electrode surface after 6 h of particle loading.

Fig. 11 shows the particle collection efficiency of the present wet electrocyclone under the same operation and loading conditions as the dry electrocyclone. After 6 h of loading, collection efficiencies were measured to be 75.1–84.7%, which were comparable to 77.1–89.4% at the initially clean condition for particles with $22.1 \leqslant d_p \leqslant 805.8$ nm. That is, the continuous cleaning water of 37 L/min per collection surface area (0.59 m^2) was able to wash the collection electrode surface clean. The water mist was also capable of cleaning the discharge electrodes. Therefore, a high collection efficiency of the present wet electrocyclone under heavy particle loading conditions can be maintained by using both cleaning water and water mist. In the future, the collection efficiencies can be further increased to 90.6–98.6%, 93.3–98.8%, and 95.1–98.8% ($22.1 \leqslant d_p \leqslant 805.8$ nm) by increasing the applied voltage to

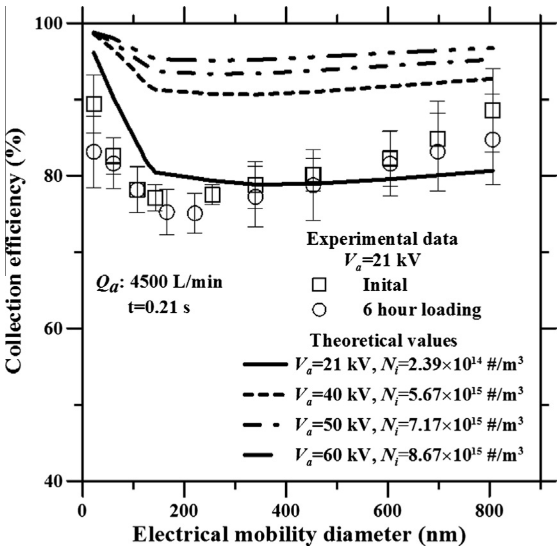

Fig. 11. Collection efficiency for OA particles in the wet electrocyclone at different TiO_2 loadings. The applied voltage and aerosol flow rate are 21 kV and 4500 L/min, respectively.

40, 50, and 60 kV, respectively, as predicted by the present model and shown in Fig. 11.

The cleaning water flow was shown to decrease the pressure drop in the wet electrocyclone. The measured pressure drop of the wet electrocyclone was increased from 0.2 to 4.05 cm H_2O with an increasing aerosol flow rate from 1000 to 4500 L/min. The experimental data of pressure drop are in good agreement with the theoretical values calculated by using the mathematical model of Dirgo [33] with the deviation of 0.02–0.06%. After supplying cleaning water, the pressure drop was found to decrease to 0.2–3.3 cm H_2O, which was much lower than that of 20.3–25.4 cm H_2O in a typical high efficiency cyclone because the uniform flowing water film reduced the air friction force on the collection electrode surface [34].

Field tests were first conducted at the aerosol flow rate of 4500 L/min and the applied voltage of 18 kV under initially clean condition. The major element of particulate matters was analyzed to be SiO_2 by using NIOSH method 7601 [35]. The mass median aerodynamic diameter (MMAD) at the inlet and outlet of the wet electrocyclone are 221 and 207 nm, respectively, as shown in Fig. 12a. It is obvious that the exhaust gases emitted from this semiconductor factory contain much more submicron particles than coarse particles.

The present wet electrocyclone was further used to conduct the field test at the aerosol flow rate of 4500 L/min and the applied voltage of 18 kV for 14 days of continuous operation. When the water mist is not supplied to clean the discharge electrodes, as shown in Fig. 12b, the total collection efficiency in the wet electrocyclone is decreased from 92.5% to 85.5% in 14 days due to particles accumulated on the tips of the discharge electrodes, which results in a reduction of ion current and electric field strength. By supplying water mist, the total collection efficiency can be maintained to be 93.0% after 14 days of continuous operation, which is comparable to 95.0% at the initially clean condition (Fig. 12b). These results again suggest that continuous cleaning water and water mist are able to maintain high efficiency of the present wet electrocyclone for a long-term operation.

The experimental total collection efficiency for SiO_2 is slightly higher than the predicted value of 80.1% (data not shown) with a deviation of 14.9%, and also higher than the experimental values for micro-Al_2O_3 obtained in the laboratory. It is because the MMAD of SiO_2 of 221 nm is much smaller than micro-Al_2O_3 of 10.2 μm, and the inlet number concentration of SiO_2 (apparent ρ_p = 0.04 g/cm^3 [36]) of 1.11–2.77 $\times$ 10^7 #/cm^3 emitted from the exhaust stack of an optoelectronic company is much higher than micro-Al_2O_3 (apparent ρ_p = 0.267 g/cm^3 [37]) of 12.8 #/cm^3 dispersed by the Jet-O-Mizer. The collection efficiency of the electrocyclone increases with an increasing inlet fine particle concentrations due to the following reasons: (1) high inlet fine particle concentration results in high particle space charge density, which enhances the electric field strength, and therefore, increases the particle collection efficiency [38]. (2) Fine particles agglomerate in the electrocyclone and the probability of agglomeration increases with an increasing inlet particle concentration. As a result, larger agglomerates are formed which are removed by electrostatic force with higher collection efficiency [39].

5. Conclusions

This study designed and developed an efficient wet electrocyclone to control micron and nanosized particles. The experimental results showed that the present wet electrocyclone can be used to

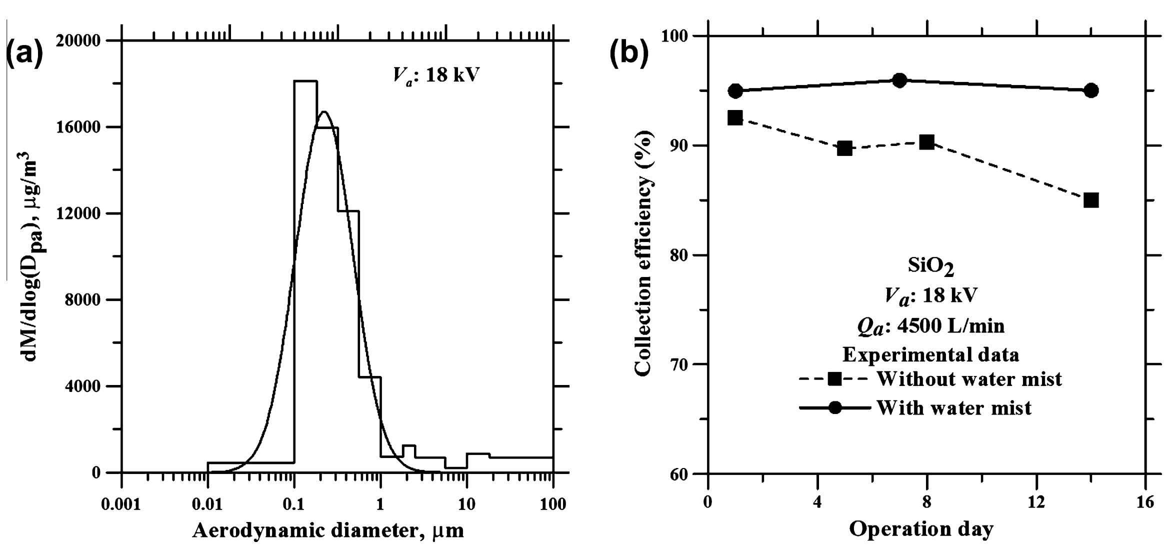

Fig. 12. Experimental results in field tests. (a) Mass concentration distribution of SiO_2; (b) collection efficiency of the wet electrocyclone for SiO_2 with and without supplying water mist during long-term operation.

control particles with $22.1 \leqslant d_p \leqslant 805.8$ nm and $0.42 \leqslant d_{pa} \leqslant 18.0$ μm at an applied voltage of 21 kV and aerosol flow rate of 1000–4500 L/min under initially clean condition. Under heavy loading conditions with the micro-Al_2O_3 loading quantity of 106 g/h, only a slight decrease of 5% in collection efficiency for OA particles with $22.1 \leqslant d_p \leqslant 805.8$ nm was found because the cleaning water and the water mist can be used to effectively clean the collection and discharge electrodes, respectively, to maintain a high collection efficiency. High particle collection efficiency was also found in field tests, in which the collection efficiencies of the wet electrocyclone for SiO_2 with $0.032 \leqslant d_{pa} \leqslant 18.0$ μm can be maintained to be 93.0% after 14 days of continuous operation.

A mathematical model was developed to predict the electric field strength, the number of particle charge, and a modified Deutsch–Anderson equation for particle collection efficiency in the wet electrocyclone. The comparison of particle collection efficiencies between the present predictions and experimental data shows good agreement with a deviation smaller than 10% for three tested particles in the size range from 0.022 to 18.0 μm. It is expected that the present modified equation can be used to facilitate the design and scale-up of the wet electrocyclone for controlling emissions of nanosized and fine particles efficiently.

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