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Application of Electrostatic Precipitator in Collection of Smoke Aerosol Particles from Wood Combustion

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ABSTRACT

A simple wire-plate electrostatic precipitator (ESP) was constructed in order to test the efficiency of collecting smoke particles from combustion of rubber-wood that is used as a source of biomass energy. The ESP contains a maximum of 15 collection plate electrodes and 20 wire electrodes per row between plates. The maximum input voltage of the Wheatstone bridge circuit using a high-voltage neon transformer was 13.5 kV (DC). The gap between plates and the distance between wires were adjustable. Results from the field test in a furnace indicate that the device could be used for a period of about one hour before cleaning the electrodes was required. The collection efficiency was decreased during the course of wood burning as the dust loading increased. Maximum efficiency was near 80% during the initial period. The distance between the collection plate electrodes had a greater influence on efficiency than the distance between the wire electrodes. The cleaning system used in this experiment was made from a row of PVC pipes to allow water to discharge radially to the plate electrodes on both sides. This system was equipped with the case of maximum collection efficiency that had a 50 mm gap between collection plate electrodes and a 64 mm distance between wire electrodes. Efficiency was increased after 120 minutes and maintained a collection efficiency of about 60%. This ESP is suitable for small and medium-sized enterprises (SMEs) to alleviate the release of detrimental chemicals such as PAHs into the atmosphere.

Keywords: Wire and plate; Biomass; Wood burning; Natural rubber; High voltage.

INTRODUCTION

Biomass is currently a major source of renewable energy. Wood is an important biomass fuel, and it has been extensively used in direct combustion. Combustion of firewood leads to pollution in the form of gases and smoke particles, which are composed of various chemical components. Incomplete combustion results in the formation of polycyclic aromatic hydrocarbons (PAHs) and other chemical compositions (Furuuchi *et al*., 2006; Bai *et al*., 2007; Tekasakul *et al*., 2008). PAHs include hundreds of compounds that are carcinogenic, especially those that contain four to six aromatic rings. This includes Benz (a, h) anthracene, chrysene, and benzo (a, e) pyrene. Factory workers who are exposed to PAHs may develop cancer and experience other negative health effects (IARC, 1982; Kogevinas *et al*., 1998; Fracasso *et al*., 1999; Straif *et al*., 1999; Galka *et al*., 2004; Parent *et al*., 2005).

In Thailand and many other Southeast Asian countries, rubber-wood (*Hevea brasiliensis*) has been extensively used in various industries (Kush *et al*., 1990; Doo-ngam *et al*., 2007; Promtong and Tekasakul, 2007, Chomanee *et al*., 2009). Combustion of rubber-wood results in large emissions of PAHs (Furuuchi *et al*., 2006; Bai *et al*., 2007; Tekasakul *et al*., 2008; Chomanee *et al*., 2009). Hence, measures taken to control or reduce particulate matters emitted from wood combustion is necessary. Several well-known devices used to collect aerosol particles include filters, gravitational settling chambers, centrifuged cyclones, scrubbers, and electrostatic precipitators, etc. These methods are very popular, especially the electrostatic precipitator (ESP). Because the smoke particles from wood combustion are in the submicron range and the concentration is variable, the most effective collection device technology is a corona discharge device or the ESP (Kalasee *et al*., 2003; Kocik *et al*., 2005; Tekasakul *et al*., 2006; Intra *et al*., 2007; Intra *et al*., 2010). Particle collection by this technique is advantageous

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because of its high collection efficiency (especially for small particles) and small pressure drop. Another important advantage is that it can be operated with very small energy consumption.

Numerous attempts have been made to use this method experimentally in order to collect aerosol particles in several applications (Zukeran *et al.*, 1997; Kim and Lee, 1999; Jedrusik *et al.*, 2001; Laskin and Cowin, 2002; Jedrusik *et al.*, 2003; Kalasee *et al.*, 2006; Srisang *et al.*, 2006; Intra *et al.*, 2007; Kalasee 2009; Intra *et al.*, 2010). Extensive review of electrostatic devices for exhaust gas cleaning was provided by Jaworek *et al.* (2007). Effects of dust loading on collection performance of a wire-plate type electrostatic precipitator have also been studied. A study by Chang *et al.* (1998) showed that the collection efficiency decreased with accumulation of dust on the collection surface and increased with applied voltage up to 10 kV.

Although many attempts have been made to use the ESP for removal of aerosol particles from biomass combustion (Kalasee *et al.*, 2003; Kocik *et al.*, 2005; Tekasakul *et al.*, 2006; Intra *et al.*, 2007; Kalasee 2009; Intra *et al.*, 2010), the collection efficiency and electrode cleaning mechanisms still need to be improved. Most of the devices are operated in dry condition where the collected particles can be removed by rapping or hammering. Because aerosol particle resulted from burning of rubber-wood used in rubber sheet smoking process contain sticky tar (Kalasee *et al.*, 2003; Nóbrega *et al.*, 2004; Podlinski *et al.*, 2006; Tekasakul *et al.*, 2006; Intra *et al.*, 2007), it is then not possible to remove them effectively by mechanical methods. A better means to remove the collected particles is then required. In the present study, a wire-plate ESP was designed to be used in local, small and medium-sized enterprises (SMEs) using rubber-wood as a fuel, in which cost of investment is a great concern. Collection efficiency of the device may not be extremely high but should be sufficient to significantly reduce the emission of the wood combustion into atmosphere. Collection efficiency of the designed ESP will be studied and geometrical parameters will be varied to obtain the highest efficiency possible. A wet-type cleaning mechanism for the wire electrodes using water spraying will be designed, and improvement of the collection efficiency will be investigated. The inclusion of the water spraying system is expected to maintain the high collection efficiency of the device. This is expected to be an advantage of the device used in the present study.

DESIGN OF THE ELECTROSTATIC PRECIPITATOR

Design

The type of ESP used in the present study was a wire-plate. This configuration was selected because it has flat collection electrodes that are easy to clean. This is very important because the emitted gas from rubber-wood combustion contains sticky tar that requires regular cleaning. The collection efficiency of the ESP can be calculated using the Deutsch-Anderson equation (White, 1963):

$$\eta = 1 - \exp\left(\frac{-V_{TE} A_c}{Q}\right) \tag{1}$$

where A_c is the collection surface area, Q is the flow rate, and V_{TE} is the terminal electric velocity, and can be calculated from:

$$V_{TE} = \frac{neEC_c}{3\pi\mu d_p} \tag{2}$$

In this equation, n is the number of charges, e is the charge of electron, E is the electrical field strength, μ is the viscosity of air, d_p is the particle diameter, and C_c is the Cunningham correction factor. The size of the particle used in this calculation is 0.68 micron which is a mass median aerodynamic diameter (MMAD) of rubber-wood smoke particles measured by Chomanee *et al.* (2009).

Particle charging is caused by thermal diffusion and field charging mechanisms. The number of charges can then be obtained with (Hinds, 1999)

$$n = n_d + n_f \tag{3}$$

The number of diffusion charges (n_d) is a function of many parameters and can be calculated from

$$n_d = \frac{d_p kT}{2K_E e^2} \ln\left[1 + \frac{\pi K_E d_p C_i e^2 N_i t}{2kT}\right] \tag{4}$$

where k is the Boltzmann constant (1.38×10^{-23} J/K), K_E is the Coulomb constant (9×10^9 Nm^2/C^2), C_i is the average ion thermal velocity (240 m/s), T is the temperature, t is the charging time, and N_i is the ion number concentration.

The number of field charges (n_f) can be calculated from

$$n_f = \left(\frac{3\varepsilon}{\varepsilon + 2}\right)\left(\frac{Ed_p^2}{4K_E e}\right)\left(\frac{\pi K_E e Z_i N_i t}{1 + \pi K_E e Z_i N_i t}\right) \tag{5}$$

where ε is the particle (assumed carbon black) dielectric constant (3.0), and Z_i is the ion electrical mobility (1.54×10^{-4} m^2/V s @100°C).

The ion number concentration can be calculated from (Intra and Tippayawong, 2005)

$$N_i = \frac{I_c d}{Z_i e u V_w h t} \tag{6}$$

Here u is the gas velocity, V_w is the voltage applied to the discharge electrode, h is the height of the collection electrode, d is the equivalent cylindrical radius and can be calculated from (Parker, 1997)

$$d = 2c\,0.18\exp\left(2.96\frac{s}{2c}\right) \quad \text{for} \quad 0.3 \le \frac{s}{2c} \le 1.0 \tag{7}$$

where s is a half of the gap between collection electrodes (d_c) and c is a half of the distance between wires electrodes (d_w), and I_c is the average corona current and can be calculated from

$$I_c = \frac{\pi\varepsilon_0 Z_i hL}{cs^2 \ln(d/r_0)} V_w (V_w - V_c) \tag{8}$$

Here ε_0 is the free-space permittivity (8.854 × 10^{-12} F/m), L is the length of the collection electrode, r_0 is the radius of the discharge electrode, and V_c is the corona onset voltage obtained from

$$V_c = r_0 E_c \ln\left(\frac{d}{r_0}\right) \tag{9}$$

The corona onset electric field, E_c, can be calculated from

$$E_c = \delta\left(32.2 + \frac{0.864 \times 10^5}{\sqrt{r_0 \delta}}\right) \tag{10}$$

where δ is the gas density.

The average velocity leaving the wood burner through the chimney pipe was 1.4 m/s, which corresponded with the volumetric flow rate of 0.0291 m^3/s. This flow rate is then corresponded with an average gas velocity in the designed ESP of about 0.063 m/s. The temperature of the gas entering the ESP was about 100°C, while the combustion temperature ranged from 500–700°C, and the pressure was 1 atm. Temperature drop occurred in the burner and connection pipe between the wood burner outlet and the ESP which is 0.5-m long. These values were used in the design of the ESP. Values of the velocity used in the design were 0.06 to 0.6 m/s to ascertain that it covered the range of the gas velocity that may fluctuate due to the natural flow behavior. When designing the ESP, an initial collection efficiency of 95% was used. This was the expected value to be obtained during the initial period when no deposition on the collection electrodes had taken place. The value was selected to be near 90% in order to provide a round number for the dimensions, which were 540 × 1,200 mm stainless steel collection plate electrodes, 75 mm gap between plates, and 85 mm distance between wire electrodes. This value of the collection efficiency was deemed suitable for use in small industries where the cost of investment is a great concern. The total dimension of the ESP was 767 mm × 1,300 mm × 645 mm, as shown in Fig. 1. It contained 15 maximum collection plates and 20 1-mm-diameter wire electrodes per row between plates. Bakelite (thermal conductivity = 16.7 W/m.K, dielectric constant = 3.7) was used as an electrical insulator between the wire and collection electrodes, as well as the outer chassis of the ESP. Details of the design criteria and requirements of the ESP are given in Table 1.

The Electrical Components

A high-voltage neon transformer (Lecip, EX230A15, 30 mA) was used to transform the input voltage of 220 VAC to 15 kVAC. A simple Wheatstone bridge circuit that rectified the AC current to DC current employed eight high voltage diodes (No. ESJC13, 9 kV, 450 mA). These diodes were encompassed in a plastic tube filled with oil to prevent discharge at high voltages. The simple direct current high-voltage circuit used in this study is shown in Fig. 2. Two diodes were connected in series in each branch to increase the voltage two folds (18 kV) before forming the bridge. The negative polar of the Wheatstone bridge

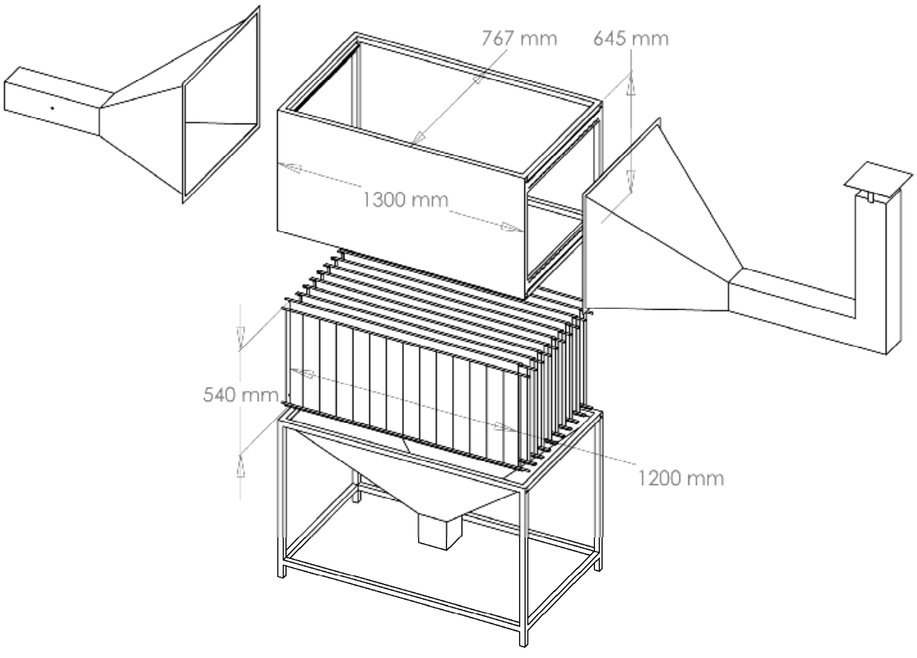

Fig. 1. The electrostatic precipitator.

Table 1. Criteria and requirements used in the design of the ESP.

Parameter	Value
T (K)	373
d_p (micron)	0.68
V_W (kV)	13.5
u (m/s)	0.06–0.6
η (%) @0.6 m/s	> 95

circuit was applied to copper wire electrodes, and the collection plates of the ESP was grounded. The high voltage was measured using a high voltage probe (KAISE, SK-863) equipped with a 50-kV high voltage probe with a 1000-times divider (KAISE model 853). Output DC voltage of this full-wave bridge rectifier circuit without capacitor filter showed a waveform rather than the exact direct behavior, and its rms value was about 13.5 kV corresponding to the previous research study (Tekasakul *et al*., 2006). This output value was used for all experiments.

Experimental parameters, including the gaps between collection electrodes (d_c) and the distances between wires electrodes (d_w), varied in the experiment and are shown in Table 2. Prediction of the voltage-current of the designed ESP shown in Fig. 3 indicates that the gap between collection electrodes (d_c) has greater influence than the distance between wires electrodes (d_w). Onset of corona for each case is shown in Table 3. In any case, the onset voltage is far lower than the designed operating voltage (13.5 kV). This ensures the onset of corona discharge at the operating condition. It also shows that the current was increased with the applied voltage. Prediction of the numbers of charges and corona onset values from the designed ESP are also given in Table 3.

EXPERIMENT

The experimental setup to determine collection efficiency of the ESP is shown in Fig. 4. The ESP was connected to the wood combustion furnace where 4 kg of rubber-wood was burned. Aerosol sampling was conducted at the upstream and downstream locations of the ESP using HEPA filters. The input voltage for the ESP was 220 VAC, which is equivalent to the output of 13.5 kVDC. The collection efficiency (η) can then be calculated from:

$$\eta = 1 - \frac{c_{exit}}{c_{inlet}} \qquad (11)$$

where c_{inlet} and c_{exit} are the mass concentrations of particles at the inlet and exit of the ESP. Sampling flow rates for both lines were controlled at 24 L/min by control valves, orifice meters, and a vacuum cleaner used as a suction pump as shown in Fig. 4. The sampling flow rate is corresponded to the average velocity of 0.079 m/s. This is in the range of the actual gas velocity in the ESP, ranging from 0.04 to 0.2 m/s, equivalent to the flow rate of 0.02 to 0.09 m^3/s, which covers the designed value. The large variation of the velocity is due to the fact that the flow was natural. The condition of isokinetic sampling was approximately achieved. The variation does not significantly affect the loss or gain of the sampled particles as the MMAD of smoke particles is very low (0.68 micron). The maximum Reynolds number in the ESP was about 1.0×10^4 which indicated that the flow was laminar.

The first sampling was performed 15 minutes after the start of wood burning. Samplings lasted 15 minutes each and were taken with 15 minute intervals between each sampling for five hours (10 samplings were collected for each line). The 110-mm-diameter HEPA, or high efficiency particulate air filters (Cambridge, glass fiber filter), were used in all samplings. The filters were treated in a control environment (25°C and 50% RH) for 72 hours before and after the sampling.

COLLECTION EFFICIENCY OF THE ESP

The average concentration of smoke aerosol particles entering the ESP from 110 samplings was 498.1 mg/m^3. (S.D. = 340.7 mg/m^3). The flow rate of gas varied from 0.02 to 0.09 m^3/s, which covers the designed value. The large variation of the flow rate was a result of the natural and uncontrolled flow. Effects of distance between wire electrodes on the ESP collection efficiency are shown in Figs. 5(a) and (b) for the gaps between collection electrodes of 75 and 50 mm, respectively. Results show that the distances between wire electrodes had an insignificant influence on the collection efficiency, although the collection efficiency for closer corona-discharge wire electrode distances were slightly higher during the first 120 minutes when the collection electrodes were still clean.

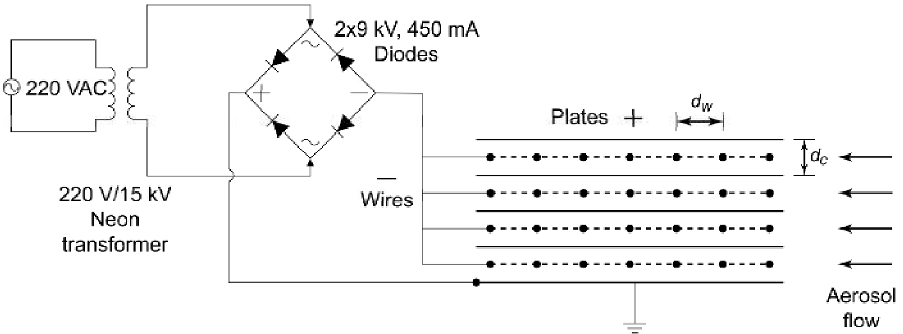

Fig. 2. Diagram of the direct current high-voltage circuit.

Table 2. Parameters for the experiment to determine collection efficiency of the ESP.

Gap between collection electrodes, d_c (mm)	Distance between wire electrodes, d_w (mm)	Number of wires per row	Total collection electrodes
50	85	15	15
50	64	20	15
75	85	15	10
75	64	20	10

The collection efficiency was continuously reduced during the course of the experiment because of the deposition of aerosol particles and emission of tar from wood combustion, which reduced the strength of the electrical field.

Thirty minutes after initiation of the experiment, the collection efficiencies were 77.6% and 73.9% where the

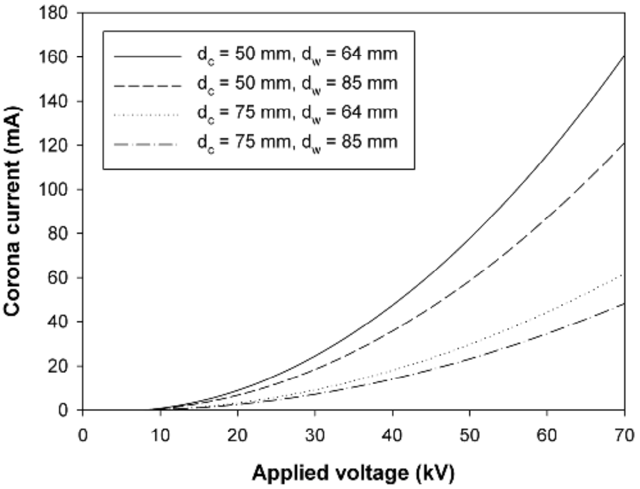

Fig. 3. Current-voltage prediction of the designed electrostatic precipitator.

Table 3. Prediction of the numbers of charges and corona onset values from the designed ESP.

Parameter	d_c = 50 mm d_w = 64 mm	d_c = 50 mm d_w = 85 mm	d_c = 75 mm d_w = 64 mm	d_c = 75 mm d_w = 85 mm
$N_i t$ (ions/m^{-3} s)	8.1808×10^{14}	6.1546×10^{14}	4.6000×10^{14}	3.2756×10^{14}
n_d	69.48	67.32	65.11	62.53
n_f	77.89	77.85	51.86	51.85
n	147.37	145.17	116.97	114.38
E_c (V/m)	3.718×10^6	3.718×10^6	3.718×10^6	3.718×10^6
V_c (V)	7,981.4	7,977.9	9,056.1	8,787.1
I_c @13.5 kV (mA)	2.760	2.080	0.870	0.716

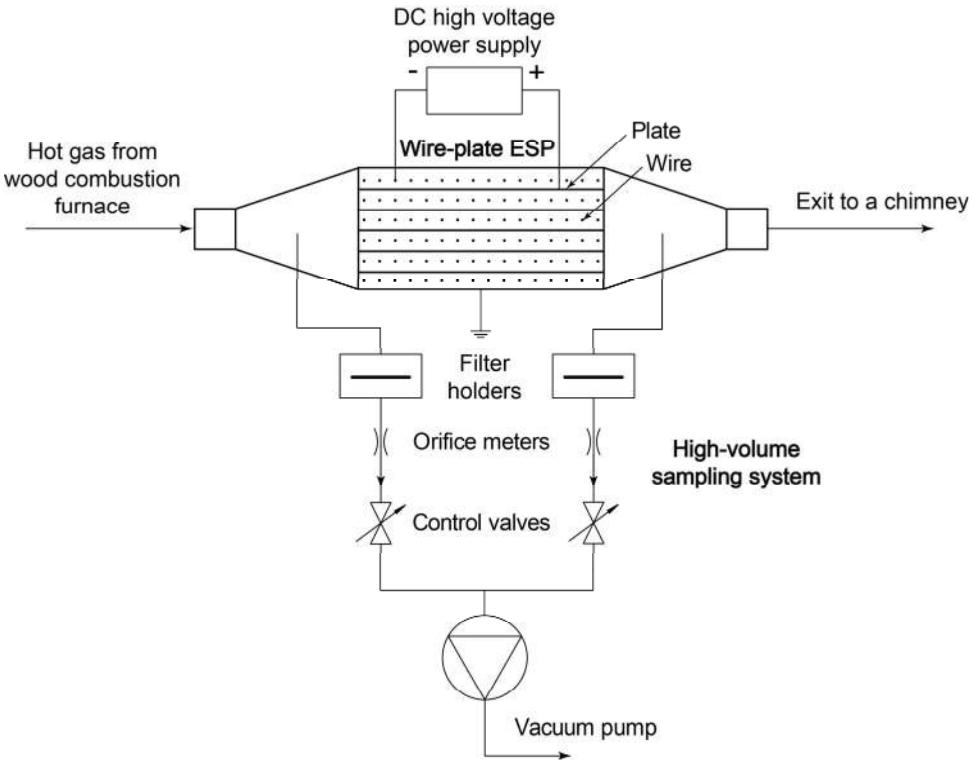

Fig. 4. Diagram of the gas sampling equipment.

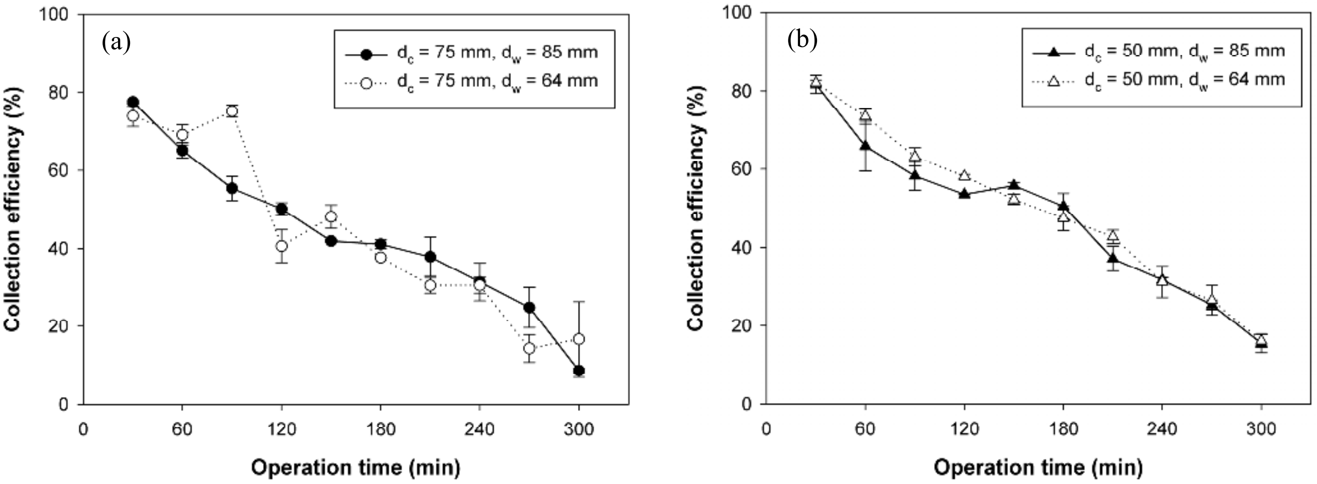

Fig. 5. Collection efficiency of the ESP for constant gap between collection plate electrodes (d_c) and variable distance between wire electrodes (d_w) (a) d_c = 75 mm, d_w = 85, and 64 mm. (b) d_c = 50 mm, d_w = 85 and 64 mm.

gap between collection electrodes was constant at 75 mm, and the distances between electrode wires were 85 mm and 64 mm, respectively. After 300 minutes, the efficiencies were reduced to 8.7% and 9.7%, respectively. When the gap between collection electrodes was constant at 50 mm, and the distances between wire electrodes wires were 85 mm and 64 mm, the collection efficiencies at 30 minutes after initiation of the experiment were 81.7% and 82.1%. They were reduced to 15.5% and 16.1%, respectively, after 300 minutes.

Results from the variable gap between collection electrodes provide a clear distinction about the distance between wires electrodes of 85 and 64 mm, respectively, which are shown in Figs. 6(a) and (b). When the gap was reduced, the collection efficiency improved. The trend remained constant for the entire duration of 300 minutes and became clearer for the smaller distances between wires. The smaller distances between wires may have caused a higher concentration of ions, even at the dust-loaded condition.

Comparison of the collection efficiency for all four cases is shown in a single graph in Fig. 7. The efficiency was plotted against the dust-loading parameter (cvt) where c is the particle mass concentration, v is the aerosol velocity in the collection device, and t is the collection time. The collection efficiency for every case was shown to be maximal during initial periods and decreased as dust loading increased. The discharge current was retarded due to particle deposition on the surface of the collection electrodes during five hours of operation in the test furnace. Higher collection efficiency was found to take place when the gaps between collection plate electrodes and between the wires electrodes were reduced. When the gap between the collection plate electrodes was reduced to 50 mm, the distance between the wire electrodes played an insignificant role in enhancing efficiency. In practice, 50 mm is the minimum distance that should be used for safe operation of a simple and economical ESP. The efficiency declined from about 80% to 70% when cvt was about 2 kg/m^2, which corresponds to about two hours of actual operation

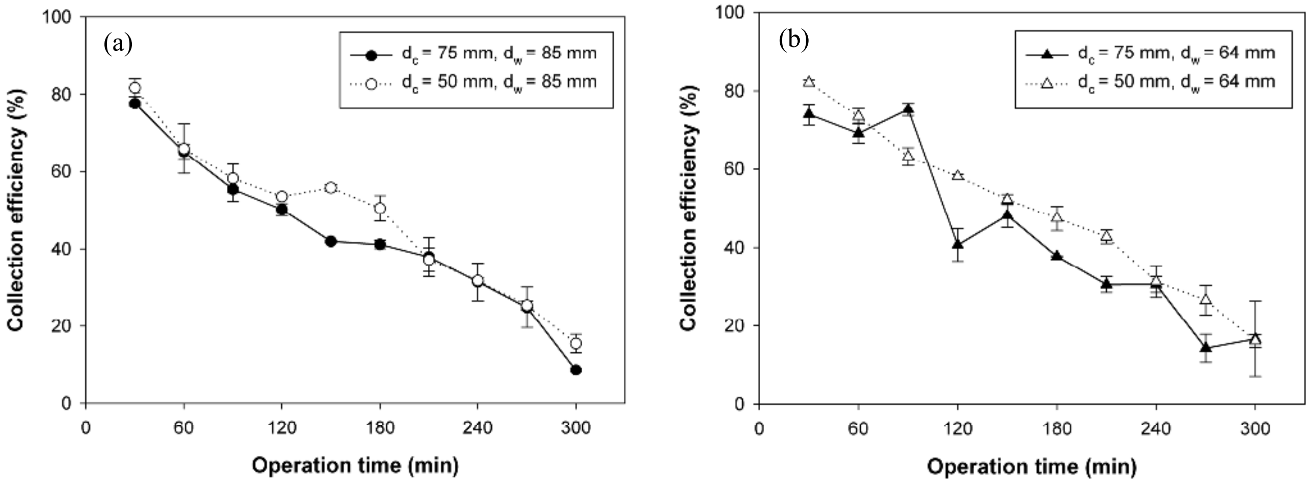

Fig. 6. Collection efficiency of the ESP for constant distance between wire electrodes (d_w) and variable gap between collection plate electrodes (d_c) (a) d_w = 85 mm, d_c = 50 and 75 mm. (b) d_w = 64 mm, d_c = 50, and 75 mm.

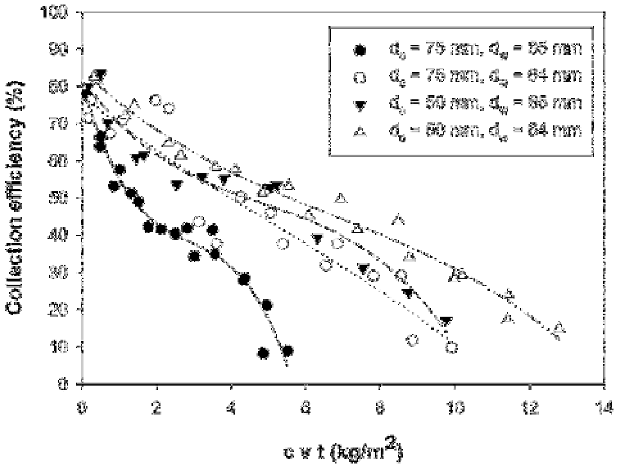

Fig. 7. Comparison of the ESP collection efficiency at same dust-loaded condition.

time. When used in a real situation, electrode cleaning is then required at least after every two hours in order to ensure sufficient collection efficiency. This will be described in the next section.

EFFICIENCY IMPROVEMENT BY PLATE CLEANING

The cleaning system used in this experiment was made from a row of 1/2-inch PVC pipes (thermal conductivity = 0.19 W/m.K dielectric constant = 3.0), as shown in Fig. 8. Each pipe was drilled by 3-mm holes along two rows in order to allow water to discharge to the plate electrodes on both sides. A centrifugal pump (200 L/min, Head 10 m) was used to supply water to the system. Water was introduced from both ends of the pipes once every hour, and each spraying time lasted 15 minutes. The cleaning system was equipped with the case of maximum collection efficiency discussed in the preceding section; the gap between collection plate electrodes was 50 mm, and the distance between wires electrodes was 64 mm.

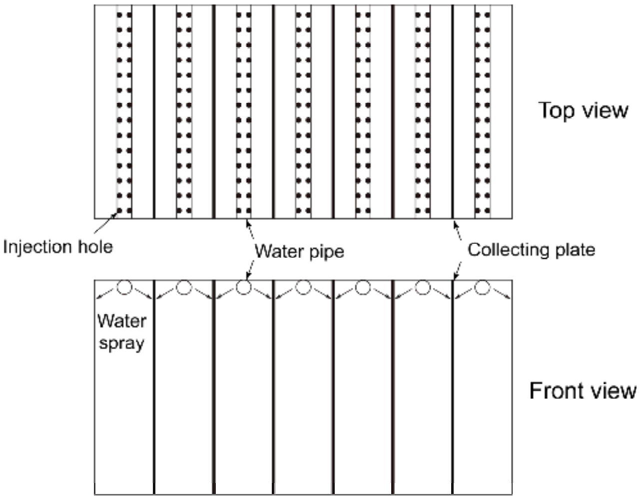

Fig. 8. Diagram of cleaning system of the ESP.

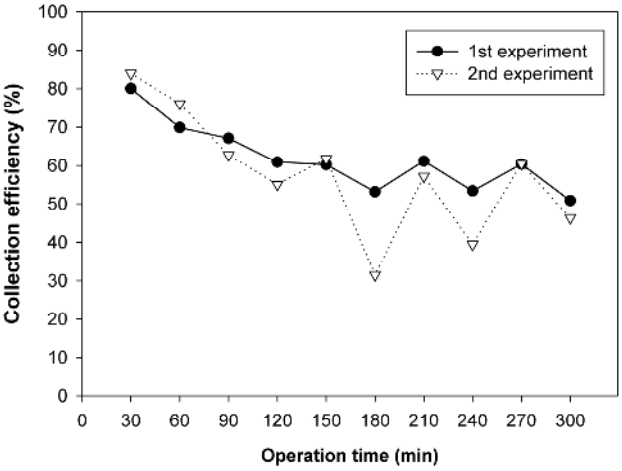

Fig. 9. Collection efficiency of the ESP equipped with a cleaning system.

Results from two experiments are shown in Fig. 9. During the first two hours, the collection efficiency decreased at a slower rate than when no cleaning system was equipped. It dropped from more than 82% at 30 minutes to about 60% after 120 minutes. The efficiency could not be maintained at the initial value because the smoke contained sticky tar, which was attached to the collection electrodes, and it was difficult to remove. However, after 120 minutes, the collection efficiency was raised to about 60% by the water spraying. The reduction of tar resulted from the combustion and the ESP could effectively remove the smoke particles. Cleaning effectiveness can be seen in Fig. 10, which displays the collection electrodes before and after the water spraying. Fig. 10(a) shows the particle trails at the end of the operation (after 5 hours) when no cleaning system was installed. Most of the particles were attached to the plate in the vicinity of the discharge electrodes resulting from high electrical filed strength in the area. The particles were effectively removed by the cleaning mechanism as shown in Fig. 10(b). It shows the clean surface of the collection electrode at the end of the operation (after 5 hours) when the cleaning system was installed and used. The ESP designed in the present study is an improved version from previous investigations. It has a higher collection efficiency than the design from the previous work, in which the collection efficiency was reduced to about 40% under the dust-loaded condition (Tekasakul *et al.*, 2006). The collection efficiency of an ESP designed by Kalasee (2009) used for the same purpose was about 40–50%, and the cleaning system was not installed. Moreover, the cleaning mechanism designed in the present study can prolong the use of the ESP, and a dust-loaded condition can be avoided.

In consideration of finances, the fixed cost of the ESP is about US$ 1,100. The electricity and water usages for the equipment are 0.7 kW-hr and 6.0 m^3 for 10 hours of operation per day. This results in a total monthly cost of US$ 70 in Thailand. This is affordable to local SMEs who cannot afford to pay for high-efficiency sophisticated ESPs, which are very expensive but able to effectively protect the environment.

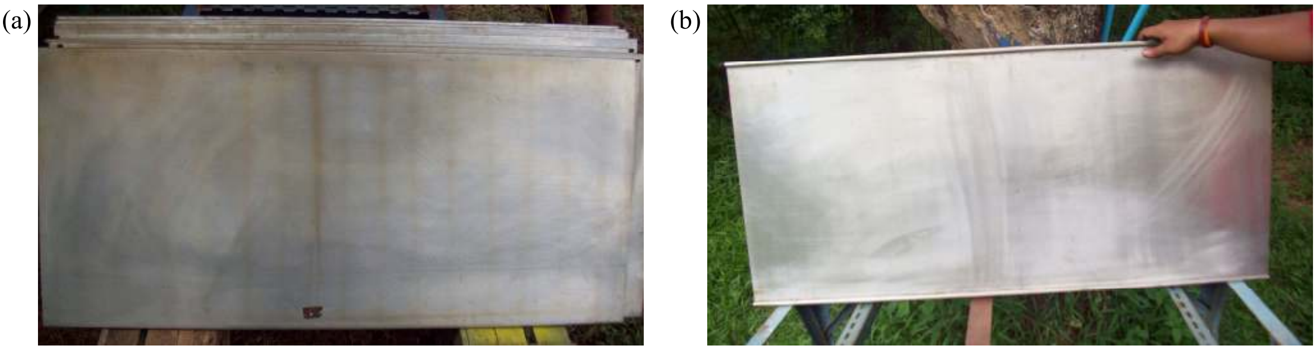

Fig. 10. Pictures of the collection electrodes (a) before the cleaning, and (b) after the cleaning.

CONCLUSION

The maximum collection efficiency of the designed ESP was found to be near 80% during the initial period. The collection efficiency decreased as the dust loading increased. Results show that the gap between the collection plate electrodes has a greater influence on efficiency than the distance between the wire electrodes. In practice, minimal distance between the collection plate electrodes should be about 50 mm for safe and efficient operation. The efficiency was reduced from about 80% to 70% when *cvt* was about 2 kg/m^2, which corresponds to about two hours of operation. The efficiency of the cleaning system increased after 120 minutes. Electrode cleaning is required after every hour in order to ensure sufficient collection efficiency, which is a process that maintains a level of about 60%. The ESP used in this study is suitable for the small and medium-sized enterprises (SMEs) using wood combustion for production because it is low in cost and the efficiency is sufficient to alleviate emissions of detrimental chemicals like PAHs into the atmosphere.

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