

Demonstration of a Modular Electrostatic Precipitator to Control Particulate Emissions from a Small Municipal Waste Incinerator

Panich Intra[†], Artit Yawootti* and Nakorn Tippayawong**

Abstract – Incineration is conceptually sound as a waste treatment technology. There is, however, concern over its emissions when it is improperly designed and operated. An electrostatic precipitator is one of the most commonly used devices to control particulate emissions from boilers, incinerators and some other industrial processes. In this work, a modular electrostatic precipitator with sizing of 1 m × 1 m × 1 m was developed for removal of particulate matter from the exhaust gases of a small waste incinerator. Its design was based on a simple wire-and-plate concept. The corona discharge wires were connected to a positive high-voltage pulse generator, while the collection plates were grounded. The high-voltage pulse generator was used to produce the corona discharge field between the individual discharge wire and the collection plate. The particulate-laden exhaust gas flow was directed across the corona discharge field. The charged particles were deflected outward and collected on the plate. The collection efficiency was evaluated as a mass loading ratio between the difference at the inlet and the outlet to the particulate loading at the inlet of the precipitator. The collection efficiency of this modular electrostatic precipitator design was approximately 80 %.

Keywords: Electrostatic precipitator, Particulate matter, Pollution control, Waste incineration

1. Introduction

Continual growth in population, the increasing rate of waste generation per capita, and the decreasing availability of suitable disposal sites all combine to indicate that incineration will increasingly become dominant method of waste management, especially in municipality level. Incinerators will likely be located close to population centers in order to reduce operating and hauling costs. High emissions of noxious gases as well as particulate matter are a major drawback of this method. Effective control of this source of atmospheric pollution is thus an important goal.

In waste incineration, an electrostatic precipitator (ESP) is one of the most common devices used successfully to remove suspended particulate matter in exhaust gas [1-4]. Reviews of its recent development are given by Mizuno [3] and Jaworek et al. [4]. Its principle is to separate particulate matter from an exhaust gas by corona charging the particulate matter and driving them toward the collection plate using electrical forces. The ESP has the following advantages; it can be operated over a wide range of gas temperatures, from ambient (35°C) to 850°C; it can achieve high collection efficiency, typically above 99%; its

construction is robust and reliable; and it requires low maintenance [1, 2].

However, an ESP with high removal efficiency is normally large in size, suitable only for industrial applications. It can be complicated and very expensive to operate. There have been several studies and developments on ESP applied to exhaust after-treatment system of biomass furnaces. Most published reports are limited to the characteristics of ESP in large-scale applications [5-9]. Little has been said about the installation of this pollution control device in small-scale biomass fired furnaces [10-12]. Affordable and practical technology is not available for small combustion systems such as a small waste incinerator adopted at municipality level in Thailand. In our previous work [11], a simple, compact and cost effective ESP has been specifically designed and constructed for removal of particulate matter from biomass burning in small combustors. Prototype device was installed and operated successfully. It was reported that over 70 % collection efficiency can be achieved. However, major shortcoming of the exhaust gas from biomass furnace is the presence of tar, a complex mixture of polyaromatic hydrocarbons. Tar from the flue gas deposited on the discharge electrodes was found to adversely affect the discharge current and reduce the collection efficiency of the ESP. Technique for simultaneous collection of particulate matter and tars was therefore required. DC pulsed power supply to generate electric field inside the ESP is of particular interest. It can generate higher electric field strength and ion concentration than DC power supply without excessive breakdown, hence, enhance particle

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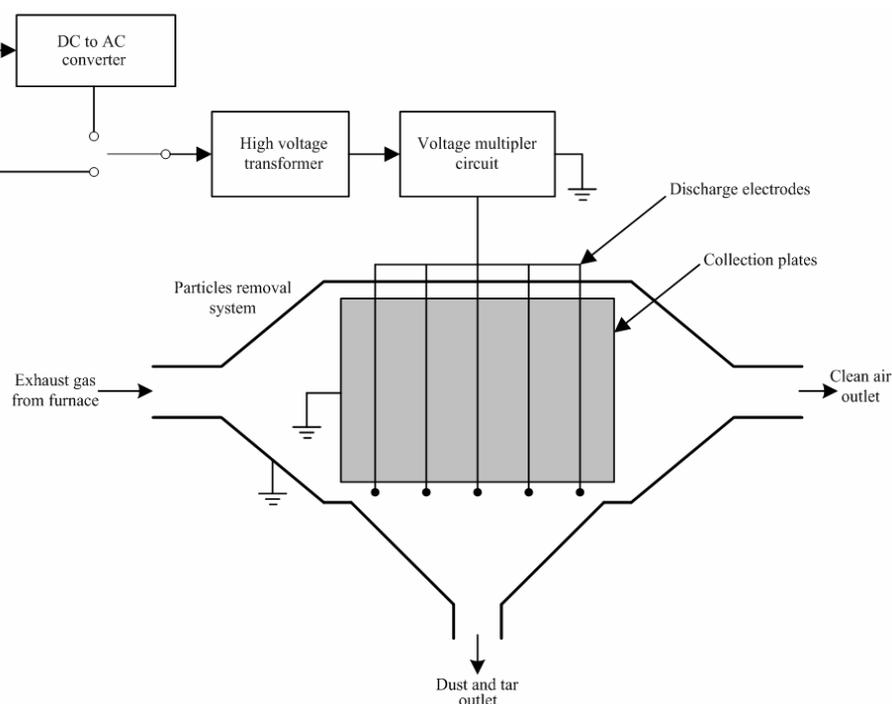


Fig. 1. Schematic diagram of the modular ESP arrangement.

charging due to larger electrical mobility of ions, and improve the ultrafine particle collection efficiency. The DC pulsed power supply has been proved to reduce black corona with high resistivity tar and particulate matter [13]. The present study is among the first to tackle this shortcoming, focusing on design, construction, and installation of a simple, compact and cost effective ESP with DC pulsed power supply capable of removing particulate matter from the stack gases of a small municipal incinerator. The ESP was modeled theoretically and tested experimentally.

2. Design of the Modular ESP

An ESP is needed to remove particulate matter in the emission gas from a waste incinerator. The primary performance requirements of the ESP are dictated by size range and mass concentration of particles as a whole: from 10 nm – 10 μm and mass concentration at the outlet of the ESP less than 15 $\mu\text{g}/\text{m}^3$. Generally, the ESP must be safe to operate and have low maintenance requirements. The primary hazard arising from the collector itself is due to the high voltage applied to the corona discharge electrodes in order to create a strong electric field within the ESP. The high voltage hazard can be minimized by properly insulating all high voltage lines and connections, isolating any exposed components, and by using insulation materials with sufficient dielectric strength to prevent arcing and short-circuiting. Fig. 1 shows a schematic diagram of the modular ESP developed in this work. It consists of four

major components: a gas inlet tube, a particulate collector, a clean gas outlet tube, and a high voltage power supply. The following paragraphs give a brief description of the rationale and design of these components.

2.1 Particulate collector

In the present study, a wire-to-plate ESP configuration was used for the particulate collector. This configuration was adopted because its collecting plates are easy to clean.

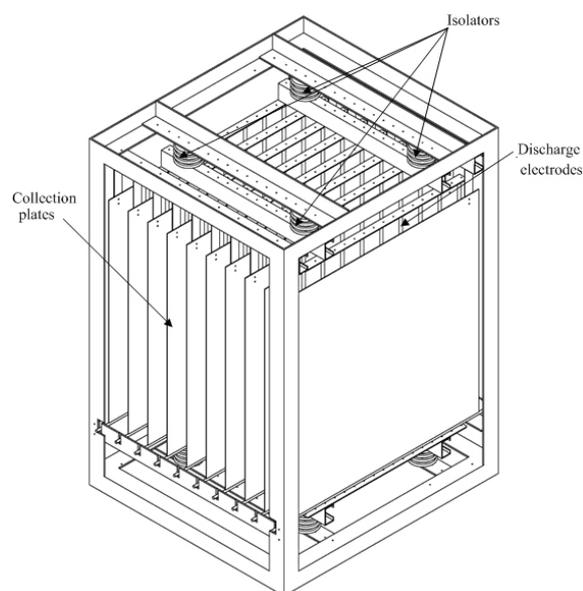


Fig. 2. Drawing of the modular ESP

Table 1. Dimensions and operating conditions of the modular ESP.

Dimensions and operating conditions	Values
Number of plates	10
Diameter of discharge electrode	3 mm
Height of collection plate	1 m
Width of collection plate	1 m
Distance between discharge electrode to collection plate	50 mm
Distance between discharge electrode to discharge electrode	50 mm
Applied voltage on discharge electrodes	20 kV

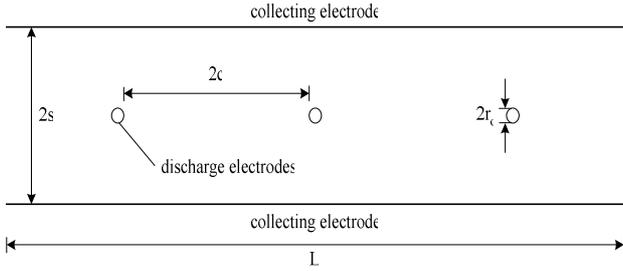


Fig. 3. Wire-to-plate ESP configuration.

The schematic of the particulate collector is shown in Fig. 2. The overall dimension was 1 m × 1 m × 1 m. The discharge electrodes are made of stainless steel rods, 2 mm in diameter and 1.1 m in length. Ten collection plates are made of steel, 1 m high × 1 m wide × 3 mm thick. Dimensions of the present particulate collector are shown in Table 1. As shown in Fig. 3, the wire radius, r_0 , the wire to plate distance, s , and the distance between the discharge wires, $2c$, were needed for the calculation of the electrical field. Plate-type configurations are described using the characteristic length, which is a function of the wire-plate distance, s , and the wire to wire distance, $2c$. The electric field, E , for plate-type ESPs is given by [2]

$$E = \frac{V}{r_0 \ln(d/r_0)} \quad (1)$$

$$d = 0.36c \exp\left(\frac{2.96s}{2c}\right) \text{ for } 0.3 < \frac{s}{2c} < 1.0 \quad (2)$$

where V is the potential difference between the discharge wires and the collection plate of the precipitator.

The corona discharge electrodes were connected to a positive high voltage pulse power supply, while the collection plates were grounded. The high voltage pulse power supply was used to produce the corona discharge field between the individual discharge electrodes and the collection plates. The particulate laden exhaust gas flow was directed across the corona discharge field. Particles were charged by collision with ions produced by the corona discharge inside the precipitator. Ions were transported by the electric field and/or by thermal diffusion. “Field charging” refers to particles charged by ions transported by the electric field. For larger particles ($>0.5 \mu\text{m}$), field charging is dominant. For smaller particles (<0.2

μm), thermal diffusion becomes dominant, known as “diffusion charging” [3]. In field charging, ions are transported to suspended particles along the field lines.

For an initially neutral particle, the average number of the elementary units of charge, n_{field} , the particle acquires in an average electric field E , is given by

$$n_{\text{field}} = \left(1 + \frac{2\varepsilon - 1}{\varepsilon + 2}\right) \left(\frac{Ed_p^2}{4K_E e}\right) \left(\frac{\pi K_E e Z_i n_i t}{1 + \pi K_E e Z_i n_i t}\right) \quad (3)$$

where ε is the particle dielectric constant, E is the average electric field strength inside the precipitator, d_p is the particle diameter, $K_E = 1/4\pi\varepsilon_0$ is the vacuum permittivity, e is the value of elementary charge on an electron, Z_i is the electrical mobility of an ion, n_i is the ion number concentration, and t is the charging time. In diffusion charging, aerosol particle will be charged by diffusion by the ions moving under Brownian motion. Thus, the average charge, $n_{\text{diffusion}}$, caused by the diffusion charging in a time period, t , by a particle radius can be found from

$$n_{\text{diffusion}} = \frac{d_p kT}{2K_E e^2} \ln\left(1 + \frac{\pi K_E d_p \bar{c}_i e^2 n_i t}{2kT}\right) \quad (4)$$

where k is the Boltzmann’s constant, \bar{c}_i is the mean thermal speed of the ions, and T is the operating temperature. Both field and diffusion charging mechanisms occur at the same time in all particles, and neither mechanism is sufficient to explain the measured charges on the particles. From empirical information, the sum of field and diffusion charges is a very good approximation for the measured charge.

In the ESP, the action of an electric force on a charged particle in an electric field produces motion. Most particles carry some electric charge, but some may be highly charged. For highly charged particles, the electrostatic force can be a few orders of magnitude greater than the gravitational force. In this study, the particle mass and gravitational effects were assumed to be negligible. Therefore, the particle velocity, v_p , in an electric field is given by the following equation:

$$v_p = \frac{n_p e E C_c}{3\pi\mu d_p} \quad (5)$$

where n_p is the net number of elementary charges on the particle as a function of particle diameter, C_c is the Cunningham correction factor, and μ is the gas viscosity.

The charged particles were deflected outward and collected on the collection plate wall. Collection efficiency of the ESP is defined as the ratio of the difference between inlet and outlet concentrations to the inlet concentration. Uniform particle distribution was assumed across the collector. The particle removal efficiency of the ESP, η , for

a given particle size could be estimated by Deutsch-Anderson equation as [14]

$$\eta = 1 - \exp\left(-\frac{v_p L}{us}\right) \quad (6)$$

where L is the length of the collection plate, and u is the gas velocity. Therefore, the mass concentration of particulate, $M_p(d_p)$, as a function of a particulate diameter at the outlet of the ESP is given by

$$M_p(d_p) = M_0(d_p) - M_0(d_p)\eta \quad (7)$$

where $M_0(d_p)$ is the mass concentration of particulates as a function of a particulate diameter at the inlet of the ESP.

A computational model was also developed to investigate the distribution of electric potential and flow velocity inside the ESP to give a better understanding of the ESP operation. Numerical simulation was performed to obtain the solutions to the model. The commercial computational fluid dynamic software package, CFDRC™ was used. This software is based on the finite volume method. Fig. 4 shows the computational results of the gas

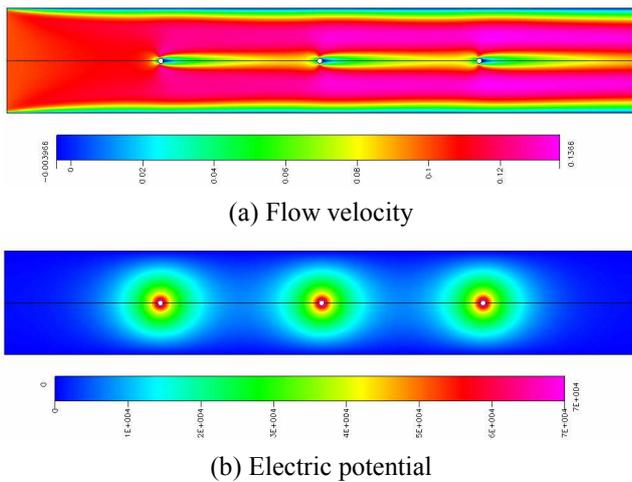


Fig. 4. CFD results of the fluid velocity distribution and electric potential in the ESP.

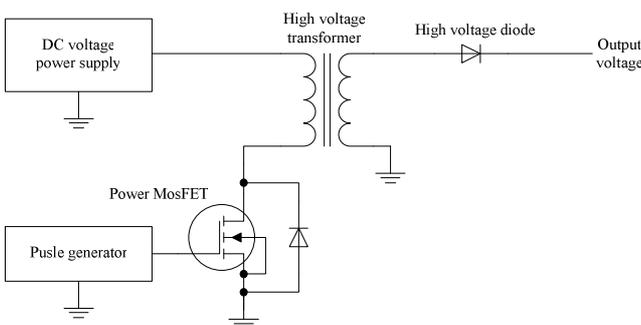


Fig. 5. Schematic diagram of the high voltage positive pulsed power supply circuit.

velocity distribution and electric potential in the ESP. High towards low intensity regions were indicated by red, yellow, and green to blue, respectively. As expected, flow separation occurred immediately after the discharge electrode, shown in Figs. 4 (a). Fig. 4 (b) shows the contours of the electric potential where the potential field formed an elliptical region around the discharge electrodes.

2.2 High voltage power supply

A high voltage power supply was used to generate high electric field strength between collecting plates and discharge electrodes. In this study, a high voltage, pulsed, positive power supply was used to generate varying impulse peak voltages and impulse frequencies to the corona discharge electrodes. The pulsed power supply had many advantages when compared with the conventional DC high voltage, including: higher peak voltage without excessive breakdown, and therefore better particle charging; control of the corona current independently of precipitator voltage by varying pulse frequency and pulse amplitude, which gives a controllable particle charging rate; a higher overall power input and improved precipitator efficiency can be achieved, and the particle migration velocity is higher because of the stronger average electric field that can be sustained under pulsed conditions [15]. A simple flyback converter was used for DC-to-DC conversion from 12 VDC to 20 kVDC. It is equivalent to that of a buck-boost converter, with the inductor split to form a transformer. As shown in Fig. 5, the converter consisted of an input DC voltage power supply, a pulse width modulated (PWM) generator, a power MosFET, a high voltage transformer, and a high voltage diode. The power MosFET works as a switch, which is turned ON and OFF by the PWM generator. During the ON-time of the power MosFET, the primary voltage of the transformer is equal to the input voltage, resulting in linear increase of the input current. During this phase, energy is stored in the transformer core. During the ON-phase, the secondary current is zero, because the diode is blocking. When the power MosFET is turned OFF, the primary current is interrupted and the voltages at the transformer invert, the diode conducts and the energy moves from the transformer core via the diode to the output. Fig. 6 shows the output high voltage waveform of the designed high voltage power supply. It was shown that the designed power supply can produce an output high voltage of about 20 kV_{peak}, output current of about 280 μA, and pulse frequency of about 30 kHz.

3. Experimental Setup

3.1 Current-voltage measurements

Fig. 7 (a) shows the setup of the experimental system for

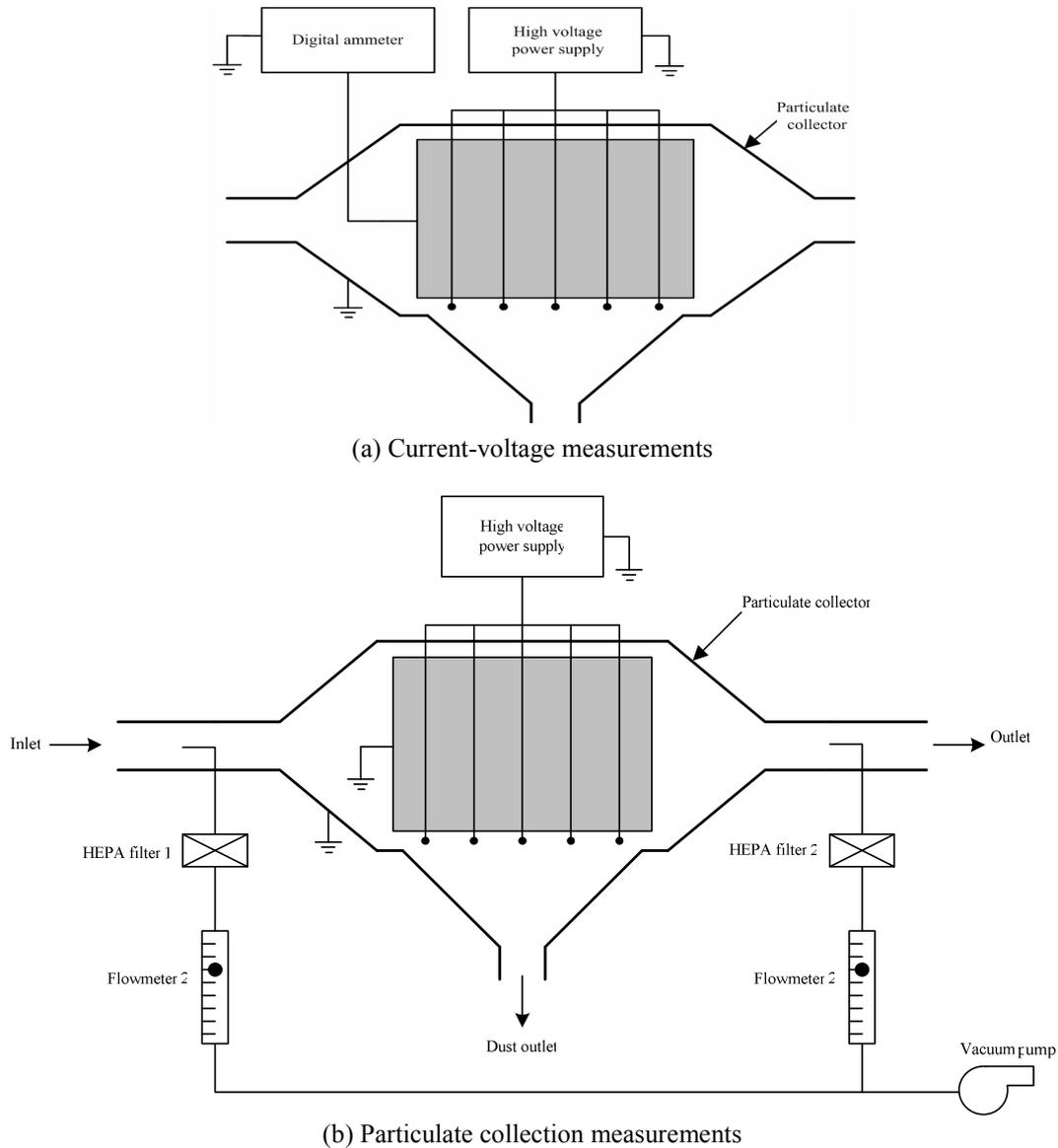


Fig. 7. Setup of the experimental system.

the current-voltage measurements of the collector. A power supply was used to maintain the positive corona voltage difference in the ESP of 20 kV. A high voltage probe (Fluke model 80K-40) and a true RMS multi-meter (Fluke model 289) were used to measure the output voltage of the power supply. The discharge current from the discharge electrodes was measured directly with the digital electrometer (Keithley model 6517) via the collection plate. Therefore, the ion number concentration in the collector could be estimated by

$$n_i = \frac{I}{eZ_i A E} \quad (8)$$

where I is the measured discharge current, and A is the surface area of the collection plate.

3.2 Particulate collection measurements

The experimental setup for the particulate collection measurements is shown in Fig. 7 (b). A small municipal incinerator with capacity of one ton per day was used to. It could be operated continuously under stable working conditions for several hours. The temperature of the emission gas entering the ESP was about 100–150 °C, while the combustion temperature ranged from 500–700 °C, and the pressure was 1 atm. A temperature drop of 400–600°C occurred in the 5 m long pipe between the incinerator outlet and the ESP. The exhaust particulate matter from this incinerator passed through the ESP. Measurements of the particle concentrations upstream and downstream of the ESP were performed by the gravimetric method. For particulate sampling, an isokinetic tube was used to measure the concentration of the particulates. The

Table 2. Operating conditions of the municipal waste incinerator.

Operating conditions	Values
Gas flow rate	1500 L/min
Gas temperature	150 °C
Pressure	1 atm

measuring points were positioned at the center of the cross section of the inlet and outlet of the ESP. The sampling flow was regulated and controlled by means of a mass flow meter and controller, typically at 5 L/min. The particulate sampling time was about 15 min. Thus, the overall collection efficiency of the ESP was evaluated with the mass loading of the particles collected on Whatman model EPM 2000 high efficiency particulate filters (HEPA) at inlet and outlet of the ESP. This efficiency is given by

$$\eta = 1 - \frac{m_{\text{outlet}}}{m_{\text{inlet}}} \quad (9)$$

where m_{inlet} is the mass loading of particulate matter at the ESP inlet, and m_{outlet} is the mass loading of particulate matter at the precipitator outlet. The basic operating conditions of the municipal waste incinerator and the parameters used for the calculations are shown in Table 2. For each set of operating conditions, measurements were repeated a minimum of three times.

4. Results and Discussion

The variation of collection efficiency with particle diameter at different operating corona voltages is shown in Fig. 8. The collection efficiency of the ESP was calculated by the Deutsch-Anderson equation for wire-to-plate type collectors (Eq. 6). The data presented covers particulate matter in the size range between 0.01 μm – 100 μm . An

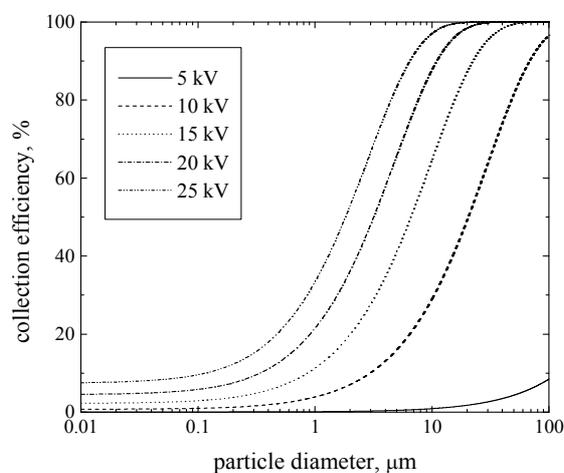
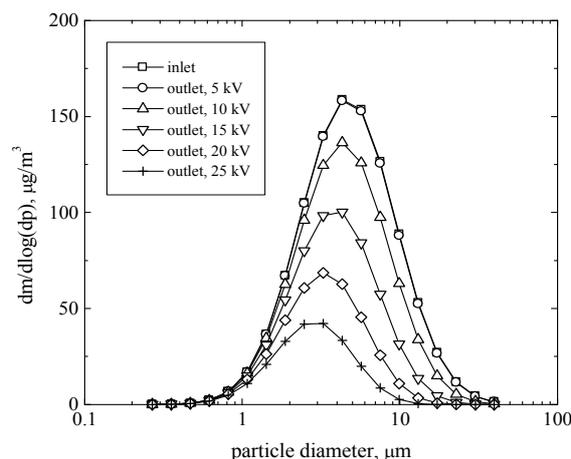

Fig. 8. Variation of collection efficiency with particle diameter at different operating corona voltages.

Fig. 9. Predicted particle size distributions upstream and downstream of the ESP.

Table 3. Current-voltage characteristics of the ESP.

Current-voltage characteristics	Values
Discharge current	280 μA
Corona voltage	20 kV
Output frequency	30 kHz
Input current	2.13 A
Input voltage	12.3 V
Input frequency	30 kHz

increase in corona voltage produced an increase in collection efficiency of the ESP. One hundred percent collection efficiency was found for a corona voltage of 25 kV for all particles larger than 10 μm . The efficiency decreased to about 10 % for particles 30 nm in diameter. It is very difficult to effectively collect particles below this size. Fig. 8 shows the theoretical prediction of particulate size distributions upstream and downstream of the ESP. A typical combustion generated particle size distribution measured by an electrical mobility spectrometer was obtained from [16]. Fig. 9 shows that the peak of the particulate mass concentration was approximately 155 $\mu\text{g}/\text{m}^3$ at the particle diameter of 4 μm . It was shown that a significant portion of the mass concentration of particulate matter (about 70 %) entering the ESP was removed from the particle-laden exhaust gas stream, prior to their release into the atmosphere.

Table 3 shows the current-voltage characteristics of the modular ESP. The high voltage positive pulsed power supply was applied to the discharge electrodes, while the collection plates were grounded. The results were evaluated for the applied corona voltage of 20 kV, the frequency of 30 kHz, and the gas temperature of 150 °C. The ion number concentration was 1.68×10^{13} ions/ m^3 at the discharge current of 280 μA . Fig. 10 shows the typical particle collection on the HEPA filters at the inlet and outlet of the ESP.

The particulate mass and collection efficiency sampled at the inlet and outlet of the ESP is shown in Table 4. At the inlet, the particulate mass ranged from 63.1 to 72.4 mg,

Table 4. Particulate loadings at the inlet and outlet of the ESP and collection efficiency.

Sampling numbers	Inlet			Outlet			Collection efficiency (%)
	Weighing of filter (mg)		Particulate mass (mg)	Weighing of filter (mg)		Particulate mass (mg)	
	Before sampling	After sampling		Before sampling	After sampling		
1	56.2	67.5	11.3	55.3	56.7	1.4	87.6
2	58.1	72.4	14.3	57.2	60.0	2.8	80.4
3	56.3	63.1	6.8	57.5	59.4	1.9	72.1

Table 5. Comparison with published literature for small-scale biomass fired furnaces.

Dimensions and operating conditions	[11]	[12]	This work
ESP type	Tube-type	Plate-type	Plate-type
Number of plates/tubes	19	15	10
Number of discharge electrodes	19	20 per row	10 per row
Diameter of discharge electrode	2 mm	2 mm	3 mm
Height/length of collection electrode	400 mm	540 mm	1000 mm
Width/diameter of collection plate	23.4 mm	1200 mm	1000 mm
Distance between discharge electrode to collection plate	10.7 mm	85 mm	50 mm
Distance between discharge electrode to discharge electrode	-	50 mm	50 mm
discharge voltage	6–8 kV	13.5 kV	20 kV
Gas flow rate	14.7 L/min	1200 L/min	1500 L/min
Operation times	60 min	~300 min	~500 min
Overall collection efficiency (% mass)	~70	~80	~80
Cost of the unit	\$500	\$1,100	\$1,000



(a) Inlet

(b) Outlet

Fig. 10. Typical particulate collected on the HEPA filter at the inlet and outlet of the ESP.

while at the outlet was they were between 56.7 and 60.0 mg. The collection efficiency was calculated to be between 72.1 to 87.6%. Reduction in collection efficiency was observed after a prolonged period of operation. It was expected that as the particulates from the flue gas deposited on the collection plate of the ESP, their build-up adversely affected the discharge current and reduced the collection efficiency. Frequent cleaning and maintenance of the collection plates and discharge electrodes were therefore required.

5. Conclusion

A small and simple ESP for the removal of particulate matter from the exhaust gases of a small incinerator was developed and investigated. Its electrical characteristics and collection efficiency were analytically and experimentally evaluated. For particles larger than 400 nm, 100 % capture efficiency was predicted. The efficiency was found to decrease with decreasing particle size. A prototype device was installed and operated successfully to a small municipal waste incinerator. The collection efficiency of the ESP was experimentally evaluated as a mass loading ratio between the difference at the inlet and the outlet, to the particulate loading at the inlet of the ESP. The average collection efficiency was found to be around 80 %.

The design and installation of the modular ESP to a municipal waste burner was successful. Its wire-plate design was not complicated, and very few problems were experienced. Comparison between this work and previously published results for small-scale biomass fired furnaces is shown in Table 5. The outcome from this work was found to be very promising. The cost of the unit is approximately \$1,000. The precipitator can operate for several hours without interruption and effectively removed 80% of the stack gas particulate matter. As fouling of the collector plates over time reduced the discharge current, frequent maintenance was recommended. To improve the efficiency, refinements that include the particulate charging characteristics, penetration efficiency, and high voltage wave form are planned for a future study.

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