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Removal of Particulates from Emissions of Joss Paper Furnaces

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ABSTRACT

In recent years, burning joss paper in temple furnaces has been noticed to be a significant cause for particulate emissions in Asia, especially in Taiwan. This study investigates feasible options of air pollution control devices (APCD) for joss paper furnaces in temples, and used a 40 kg/hr joss paper furnace for testing. This paper examined particulate removal efficiencies of two options: a bag house (capacity 30 m^3/min at 108°C) and a wet scrubber (capacity 40 m^3/min at 150°C).

The results indicate that particulate matters (PM) in the diluted flue gas at the bag-house inlet were 76.6 ± 32.7 mg/Nm^3 (average ± standard deviation), and those at the outlet of the bag-house could be reduced to as low as 0.55 ± 1.28 mg/Nm^3. An average PM removal efficiency of 99.3% could be obtained with a filtration speed of approximately 2.0 m/min evaluated at 108°C. The wet scrubber removed approximately 70% of PM, with scrubbing intensities higher than 4.0 L/m^2.s across the scrubber cross-section. For the duration of the experiment, no visual white smoke (water mist) was observed at the exit of the wet scrubber with a combustion rate of 16 kg/hr of joss paper, and the scrubbing water temperature was automatically sustained at lower than 61°C. The study concluded that both bag filtration and wet scrubbing are suitable techniques to control particulate emission from joss paper furnaces in Taiwanese temples. The bag filtration technique, while achieving higher efficiencies than the wet scrubbing technique, requires more space and cost. Examinations of bottom and fly ashes of combusted joss paper with XRD (X-Ray Diffraction) revealed the presence of calcium oxide in the fly ash, while certain metals were found in the bottom ash.

Keywords: Combustion; Particulate emission control; Bag filtration; Wet scrubbing; Joss paper.

INTRODUCTION

Burning joss paper and incense is a significant Taoist ceremonial practice in Asian countries such as Taiwan and China. Joss paper, which includes celestial money for gods and ghosts and for spirits of ancestors, is chiefly composed from bamboo and/or recycled waste paper. Widespread burning of joss paper, some of which is burnt out in the open, occurs on the first and fifteenth day of every month (according to lunar calendar) and on important Chinese festivals. The burning of joss paper, wood, and agricultural wastes has been demonstrated to significantly create particulate matter (PM) (Fang *et al*., 2003; Choosong *et al*., 2010; Ning and Sioutas, 2010; Li *et al*., 2010), metals (Lau and Luk, 2001; Fang *et al*., 2003), polycyclic aromatic hydrocarbons (PAHs) (Yang *et al*., 2005; Lin *et al*., 2008; Rau *et al*., 2008), and polychlorinated dibenzo-p-dioxin/dibenzofurans (PCDD/Fs) (Hu *et al*., 2009; Wu *et al*., 2010; Chiu *et al*., 2011; Lin *et al*., 2011). Furthermore, PAHs concentrations in ambient air during festivals were observed to be several times higher than those during other times (Lin *et al*., 2008).

Although most temples have furnaces for joss paper and unburned incense, lower combustion temperatures and poor mixing conditions in the furnaces compared to other high-efficiency incinerators result in incomplete combustion and an increase in pollutant emissions (Hu *et al*., 2009). Certain temple furnaces are equipped with air pollution control devices, such as cyclones and scrubbers, which did not show high removal efficiencies for pollutants such as PAHs (Yang *et al*., 2005).

Bag filtration is one of the most reliable, efficient, and economic methods for removing particulate matter from gases. Fabric or cloth filters in the form of tubular bags are generally used for gas filtration. A bag house consists of numerous vertical bags, 120–400 mm in diameter and 2–10 m long. The fabric cloth and the cake attached to the cloth service as a medium for filtrating out of the particulates in the influent gas. Normal filtration velocities through the cloth are 0.4–1 m/min, and removal efficiencies are generally higher than 99% for particulates greater than 0.3 μm (Rao and Rao, 1989). A filter with fibers aligned

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parallel to the direction of the airflow for removal of submicron aerosols in an indoor ventilated air stream. The removal efficiencies at face velocity of 1.0 m/s and the pressure drop of 11.5 Pa were 52% and 65%, respectively, for 0.4 µm and 0.6 µm particles. The removal efficiency for particulates with sizes less than 1 µm was approximately 51% (Noh *et al.*, 2011).

Wet scrubbers have been an encouraging option due to their high removal efficiency for coarse particles (1–2 µm in range), small onsite plot space, no problems at high temperatures, and so on. The principle collection mechanisms in a spray tower for particulate removal are impingement and interception. Only moderate contact between the gas and the liquid drops (0.5–1.0 mm in size) is effected, and the spray-type scrubber is used only for removing coarse dusts (> 1–2 µm range). Spray towers are used as coolers and as primary cleaners for fly ash and cinder removal (Rao and Rao, 1989; Ebert and Buttner, 1996; Laitinen *et al*., 2000; Peukert and Wadenpohl, 2001). With a dual flow scrubber, that is, one water-filled bubble section and one water-spray section, the removal efficiency of fly ash has been demonstrated to be almost 100% (Bandyopadhyay and Biswas, 2007). A wet fine scrubber in an iron ore sintering plant has yielded a removal of more than 65% of PCDD/F I-TEQ (Guerriero *et al.*, 2009). Bag house has also been applied to control particulate emission and to recover valuable particles in various industries, such as solid-fuel-fired power generation, bulk solid processing (Lo *et al*., 2010), milk powder plant (Gabites *et al*., 2008), and mercury capture (Cao *et al.*, 2008; Hrdlicka *et al.*, 2008).

A simple wire-plate electrostatic precipitator (ESP) was constructed to test the efficiency of collecting smoke particles from wood combustion, which is used as a source for biomass energy. The ESP contained 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 results from the field test of the furnace indicated that the device could be used for a period of approximately 1 hr after electrode cleaning. During the course of wood burning, the collection efficiency decreased while the dust loading increased. Maximum efficiency was near 80% during the initial period. Efficiency was increased after 120 min, and maintained a collection efficiency of approximately 60% (Ruttanachot *et al.*, 2011). Implied by the research, ESP, due to its required high maintenance and relatively lower efficiency for removing fine particles, is seemingly unsuitable for emission control of joss paper incineration.

The wet scrubber and bag house were expected as sound options for the removal of particulate pollutants from joss paper furnaces in temples. However, no study has focused on the topic. This paper evaluates the removal efficiencies of particulates from emitted flue gases of joss paper burning by using a bag house and wet scrubber. The results may provide useful information for temples and authorities to ascertain the feasibility of these air pollution control devices.

MATERIALS AND METHODS

Schematic diagrams of the experiment systems used in this study are shown in Figs. 1 and 2. The furnace for the joss paper incineration test was composed of steel plate, with a combustion chamber of 60 cm in diameter and 100 cm in height (chamber volume of 0.28 m^3) and a stack height of 140 cm. This study tested two types of particulate removal devices: bag house (BH) and wet scrubber (WS). Several thermal couples were set at the furnace neck, exit, and influent to the cooler for flame and gas temperature detection, as shown in Fig. 1. Before introducing the flue gas into either control device, the furnace flue gas was mixed with ambient air to cool the gas down before injecting the mixed gas into the cooler. The dilution ratio of the dilution air (ambient air) to the flue gas was controlled by regulating the feeding rate of joss paper to ensure that the influent gas to the cooler was in the range of 250–350°C. The ratio was approximately 1 to 2. The cooler had 39 finned tubes (25 cm in diameter and 100 cm in length) and 4 sets of cooling fans (50 cm propeller diameter operated at around 600 rpm) for cooling the mixed flue gas from 250–380°C down to approximately 100°C before introducing the gas to the BH (Fig. 1).

Bag House

The BH is a pulsejet filtration device with a steel enclosure (115 cm in diameter and 245 cm in height) with 23 fitted fiber bags (0.13 m in diameter and 1.6 m in length). The filter bags were composed of heat-resistant Nomex (a trade name of DuPont Co.), which was made from Nylon and can sustain a maximum operation temperature of 180°C. An influent gas flow rate of 30 m^3/min (at 108°C) was used, and the flow rate resulted in a filtration speed of 2.0 m/min. The reverse cleaning worked every 60 s by using 3–5 bars of compressed air as the pulsejet air with burst duration of 0.25 s. The filter bags required renewing while the operation pressure drop was higher than 300 mmAq (3 kPa), or the outlet air contained abnormal concentrations of dust.

Wet Scrubber

As shown in Fig. 2, the drawing fan attached to the full-scale scrubber used in this study had a maximum gas-inducing rate of approximately 20 m^3/min, evaluated at a gas temperature of 35°C. In the scrubbing section, a cross-sectional area of 0.25 m^2 (0.5 m × 0.5 m) and a height of 0.70 m were provided for the flue gas flow. According to the data, the superficial gas velocity across the cross-section was estimated at approximately 1.5 m/s, evaluated at an average gas temperature of 50°C in the scrubbing section. By the scrubbing height, a gas-liquid contact time of approximately 0.5 s could be obtained.

A circulation pump with a capacity of 40–60 L/min and 4 spray nozzles across the scrubbing section were used. According to the data, the liquid to gas ratio (Q_L/Q_G) was in the normal range of 1–3 L/m^3 for scrubbing removal of particulate matters. The Q_L/Q_G is similar to the values of > 1.34 L/m^3 when using pressure sprays, as cited in the

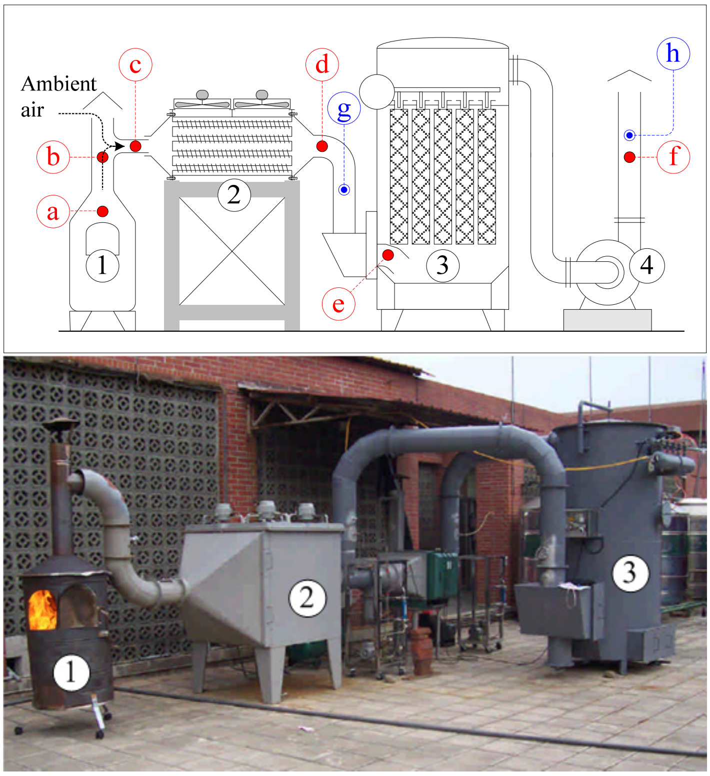

Fig. 1. Schematics and a photo of the experimental system for bag-house experiment: 1.furnace, 2. gas cooler, 3. bag house, 4. induce fan, a-f. thermal couples, g. influent gas sampling hole, h. effluent gas sampling hole.

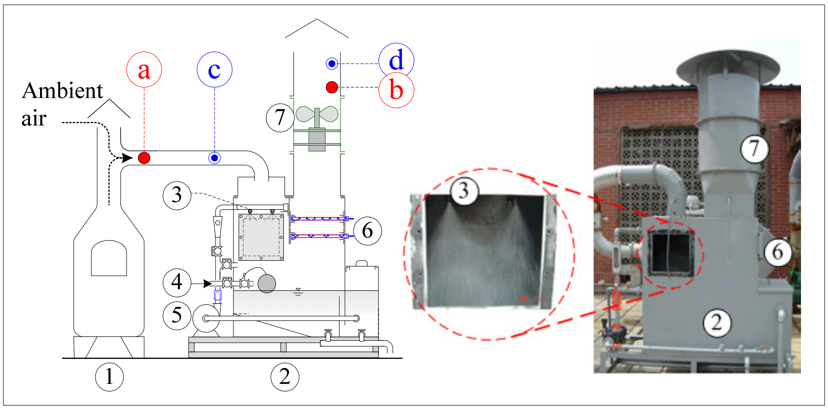

Fig. 2. Schematics and a photo of the experimental system for wet-scrubber experiment: 1.furnace, 2. scrubber, 3. spray nozzles, 4. influent water, 5. circulation pump , 6. effluent gas screens, 7. fan, a and b. thermal couples, c. influent gas sampling hole, d. effluent gas sampling hole.

literature (Laitinen *et al.*, 2000). According to the photograph shown in Fig. 2, the sizes of the sprayed water drops ranged between 0.5–1.0 mm, which is similar to those cited in the literature (Rao and Rao, 1989).

Operation

Joss paper with apparent densities of 0.26–0.48 g/cm^3 and ash contents of 2.0–3.5% were obtained from local shops. Table 1 shows the elemental analysis and heating values of the joss paper used in Taiwan (Yang *et al*., 2001). Before ignition, several sheets of joss paper were stacked in the furnace chamber. After fire ignition, either of the tested particulate removal systems was started. A specific amount (2.4–3.4 kg) of joss paper was placed into the furnace once every 4 to 5 min. Flue gas temperatures and particle matter (PM) concentrations at both the inlet and outlet of the tested BH or WS were measured. Dust collected from the bag house influent gas, clothes, and house bottom were collected for examination of the particulate size and composition. For the WS, the temperature of the recycling scrubbing water was also observed. Gases at both the inlet and outlet of the wet scrubber were sampled to measure concentrations of CO_2, CO, and NO.

Table 1. Elemental analysis and heating values of the joss paper used in Taiwan (Yang *et al.*, 2001).

Raw material for joss paper production	C (%)	H (%)	O (%)	N (%)	S (%)	Cl (%)	Lower heating value (kcal/kg)
Bamboo	40.64	6.52	39.34	0.09	0.05	0.08	4,000
Recycled paper	30.00	5.75	47.60	0.05	0.06	0.02	2,600

Analytical

Standard Methods of ASTM D4096-91 and APHA 20 2540B were applied to determine PM concentrations in the flue gas. The flue gas from the furnace was sampled with a particle sampler using a glass fiber filter (47 mm, Advantec) and the gas velocity within the gas duct was measured using a flow mater (Alnor Instrument Co., APM 100, USA). The sampling rate was adjusted to ensure that the influent gas velocity to the sampling nozzle was at approximately 95–105% in gas velocity through the duct. Compositions of the tested Joss paper were examined using a Scanning Electron Microscope (SEM) (JSM-6330TF, JEOL) and X-Ray Diffraction (XRD) (Inca X-sight 7557, Oxford). Concentrations of CO_2, CO, and NO in gases at the inlet and outlet of the wet scrubber were measured using a gas analyzer (Combustion gas analyzer, IMR3000P, USA).

RESULTS AND DISCUSSION

Bag-house Filtration

Elemental composition of bottom and fly ashes observed via XRD are shown in Table 2. In the bottom ash, a total of 49.9% and 35.5% (w/w) were found to be composed of oxygen (as metal oxides) and metals (sodium, aluminum, and calcium), respectively. Aluminum oxide was the oxide of the aluminum foil pasted on the joss paper, and calcium carbonate was found to be the major compartment in the fly ash.

The sizes of bottom ash in the furnace, fly ash collected at the bag-house inlet, ash on the clothes of the bag house, and the bottom ash in the bag house were examined via SEM, and the results are shown in Table 3 and Fig. 3. The sizes of the furnace bottom ash ranged from 50 to 300 nm, with an average of 250 nm. The sizes of the fly ashes (collected from the flue gases and in the bag house) had average sizes ranging from 20–110 nm, with an average range of 50–60 nm. SEM photos of ashes (Fig. 3) display similar appearances, although the fly and bottom ashes have different chemical compositions (Table 4).

Table 2. Elemental compositions of the bottom and fly ashes analyzed with XRD.

	Bottom Ash (%)	Fly Ash (%)
Na (Na_2O)	11.6	
Al (Al_2O_3)	23.6	
Si (SiO_2)	15.0	
Ca (CaO)		73.2
O	49.8	26.8
Total	100	100

Fig. 4 shows variations of PM concentrations and removal efficiencies of the bag house over the test time period. In the beginning 155 min, the filter clothes were clean and relatively larger clearances were present between cloth fibers, which resulted in fluctuating PM removal efficiencies in the range of 72–100%, as shown in Fig. 4(b). However, thereafter, PM removal efficiencies could be sustained at higher than 95% for most of the experimental time, with a few exceptions due to relatively lower influent PM concentrations. The high efficiencies were because most of the inter-fiber clearances had been clogged by fine fly ashes, in addition to the contribution of filter cakes accumulated on the filter clothes.

In this study, after the filtration time of 155 min, PM concentrations in the diluted flue gases at the bag-house inlet were 76.6 ± 32.7 mg/Nm^3 (average ± standard deviation, N represents the gas volume evaluated at 0°C and 1 atm), and those at the outlet of the bag-house could be reduced to as low as 0.55 ± 1.28 mg/Nm^3. According to the data, an average PM removal efficiency of 99.3% could be obtained with a filtration speed of approximately 2.0 m/min, evaluated at roughly 108°C. Fig. 5 shows the variation of PM emission factor over the test time period of 155–525 min, with the values in the range of 0.602 ± 0.278 g/(kg joss paper). Each emission factor was calculated by multiplying the measured PM concentration (g/Nm^3) with the influent gas flow rate (Nm^3/min) to the BH and the time interval of joss paper dumping (min) before the resulting mass of PM emission (g) was divided by the mass (kg) of joss paper dumped in the time interval. The fluctuating values of the emission factor might result from the variations of turbulent and thermal mixing conditions, as well as the incineration temperature of the joss paper in the furnace. However, the average value of approximately 0.60 g/(kg joss paper) can be a reference for estimating the total annual PM emission of joss paper incineration area or country, such as Taiwan, China, and other Asian nations.

Table 3. Ash sizes analyzed with SEM.

	Range (nm)	Average (nm)
Bottom ash in the furnace	50–300	250
Fly ash collected at the bag-house inlet	30–110	60
Ash on the clothes of the bag house	20–100	55
Bottom ash in the bag house	20–100	50

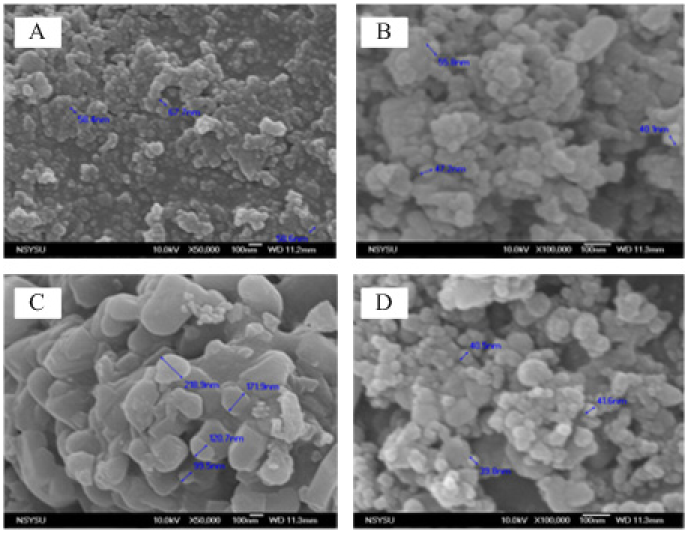

Fig. 3. SEM photos of ashes: (A) ash on the clothes of the bag house, (B) bottom ashes in the bag house, (C) fly ash collected at the bag-house inlet, (D) bottom ash in the furnace.

Table 4. Temperature variations of the gas in the system.

	Temperature (°C) of the measuring point				
	Furnace center	Furnace neck	Cooler entrance	Cooler exit	BH entrance
Mean	780	710	298	120	108
Standard deviation	22.7	54.5	43.8	10.2	10.3
Minimum	680	550	192	94	83
Maximum	829	825	417	142	128

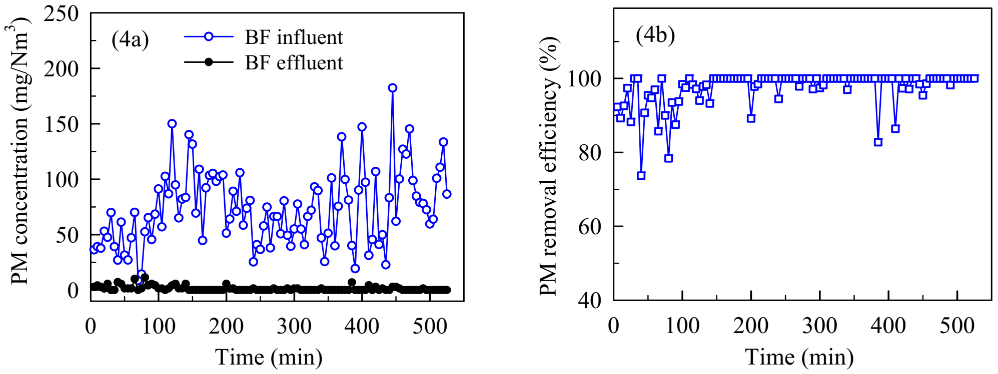

Fig. 4. Variation of (4a) PM concentrations and (4b) PM removal efficiencies by the bag house over the test time period.

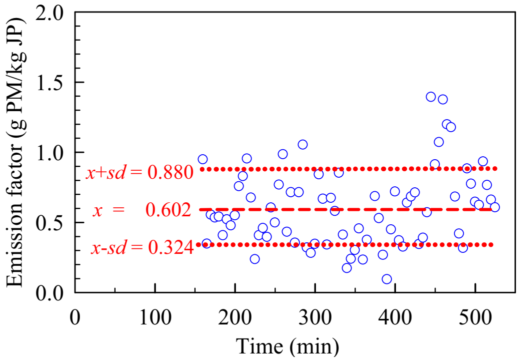

Fig. 5. Variation of PM emission factor over the test time period of 155–525 min.

Fig. 6 and Table 4 show the temperature variations of the gases in the system for the bag-house filtration test. Flame temperatures in the furnace were 780 ± 22.7°C (average ± standard deviation), and those after mixing with ambient air at the cooler entrance were 298 ± 43.8°C. Temperatures of the mixed flue gases could be cooled from 298 ± 43.8 to 120 ± 10.2°C by using the gas-gas cooler, and the cooled gas could be directed to the BH for PM removal. The BH system has evidently been properly designed and operated, with a good PM control for joss paper incineration. The installation cost of the system, including the cooler, the BH and its accessories, and the drawing fan was approximately $10,000 USD. The system can be used to remove PM from a joss paper furnace with

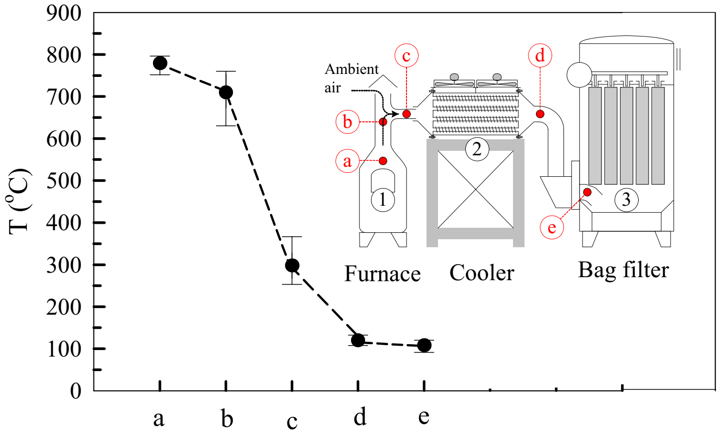

Fig. 6. Temperature profiles of the gas in the system for bag-house filtration test: a. at the furnace center, b. effluent gas from the furnace, c. influent gas to the cooler, d. effluent gas from the cooler, e. influent gas to the bag house.

an incineration rate of approximately 40 kg/hr, according to the presented experimental data.

Wet Scrubbing

Figs. 7 and 8 show the time variations of temperatures of flue gases, scrubbing water, and Q_L/Q_G ratio with water flow rates Q_G of 13.6 and 26.3 Nm^3/min, with an incineration rate of 15.3 kg/hr. In the tests, the scrubbing water flow rate (Q_L) was controlled at 20, 30, 40, 50, and 60 L/min, respectively. The purpose was to observe the removal efficiency and scrubbed gas temperature with different liquid-gas contact opportunities. Thus, the Q_L ratio was at 1.53, 2.29, 3.05, 3.82, and 4.58 L/m^3, with a Q_L of 13.1 L/min, while the Q_G ratio was at 0.76, 1.14, 1.52, 1.92, and 2.28 L/m^3, with a Q_G of 26.3 L/min. As cited in the literature, Q_L/Q_G for common spray towers is approximately 0.67 L/m^3 or 5 gal/(1,000 ft³), while that for pressure sprays is greater than 1.34 L/m^3 (Rao and Rao, 1989). The experimental Q_L/Q_G (0.76–4.58 L/m^3) were approximately 1–3 times higher than the values cited in the literature. The data indicate that with Q_G = 13.1 L/min, the gas could be cooled down from 364 ± 50.2 to 136 ± 27.1°C after passing through the scrubber, and the liquid could be sustained at lower than 61°C for the entire duration of the

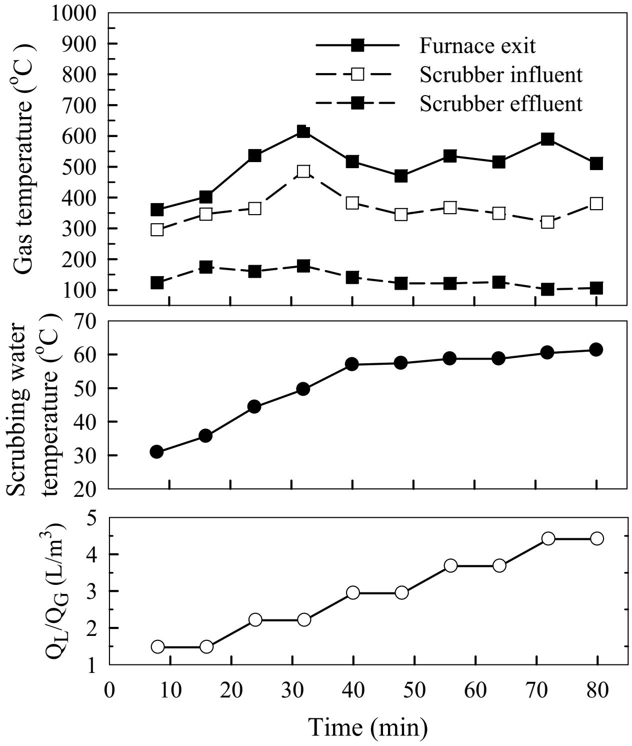

Fig. 7. Temperatures of flue gas, scrubbing water, and Q_L/Q_G ratio changing with operation time (Q_G=13.6 Nm^3/min).

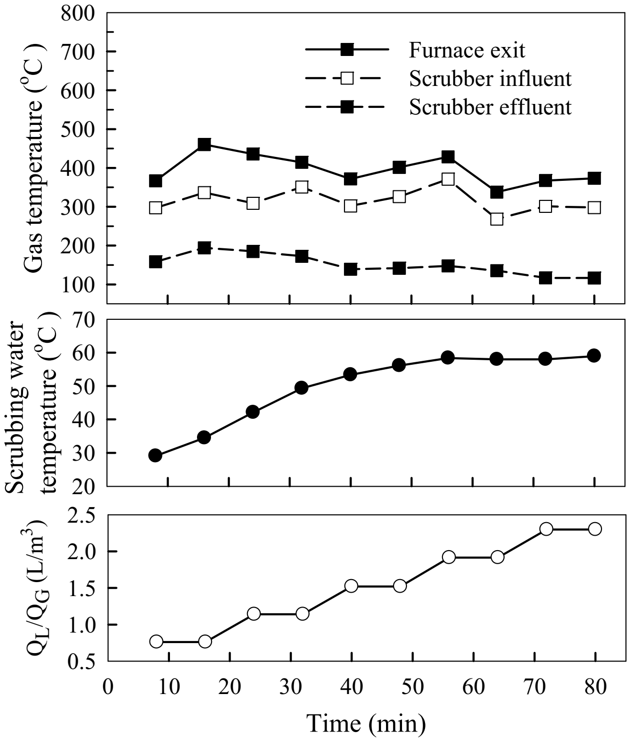

Fig. 8. Temperatures of flue gas and scrubbing water, and Q_L/Q_G ratio changing with operation time (Q_G=26.3 Nm^3/min).

test (80 min). Similar trends were observed with Q_G = 26.3 L/min; however, the scrubbed gases had temperatures of 151 ± 26.6°C due to a higher hot gas flow in the scrubber. Both exit gases from the scrubber had no visible water vapor (condensed steam), as observed in the study.

Fig. 9 shows the PM concentration data in the flue gas influent to and effluent from the scrubber and the PM removal efficiency. Data with superficial velocity U = 1.75 Nm/s over the cross-section of the scrubbing section correspond to Q_G = 26.3 Nm^3/min, and those with U = 0.88 Nm/s to Q_G = 13.1 Nm^3/min. The data indicate that effluent PM concentrations decreased with increasing scrubbing intensity L, in an operating range of 1.33–4.00 L/m^2.s (equivalent to liquid flow rates (Q_L) of 20–60 L/min). The data also show that the PM removal efficiencies increased approximately linearly in conjunction with L. A maximum removal efficiency of approximately 70% was obtained. The scrubbing intensities of higher than 4.0 L/m^2.s across the scrubber cross-section is equivalent to a Q_L/Q_G higher than 2.25 and 4.55 L/m^3, respectively, for U = 1.75 and 0.88 Nm/s. No data cited in the literature can be found for the comparison. However, the intensity of 4.0 L/m^2.s is approximately 2–3 times of the commonly used values. According to the aforementioned results, to achieve a removal efficiency of higher than 70%, operating with Q_L/Q_G higher than 3.9 L/m^3, which led to an empty bed flow rate of 0.004 m/s, would be required. In this case, consumption of the circulated scrubbing water for every1000 Am^3 of flue gases could be assumed to be 25 L, and that for 1 kg of joss paper incineration could be 2.4 L. Comparing to the 100% of removal efficiency via a dual flow scrubber with spray and bubble section, in which Q_L/Q_G ratio was controlled at 3.0 m^3/1000 ACM (actual cubic meter) (Bandyopadhyay and Biswas, 2007), the traditional scrubber used in this study could achieve only 60–70% with a similar Q_L/Q_G ratio.

Table 5 shows the concentrations of CO_2, CO, and NO in gases at the inlet and outlet of the wet scrubber and removal efficiencies. According to the data, emissions of CO and NO were both small compared with other incineration sources, such as steam boilers. The installation cost of the wet system was approximately $5,000 USD. The system can be used to remove approximately 70% of PM from a joss paper furnace with an incineration rate of roughly 16 kg/hr, according to the presented experimental data.

CONCLUSIONS

Taiwanese EPA has encouraged temple authorities to install APCD for improving air quality. Bag houses, which are able to remove more than 95% of PM, would require approximately $10,000 USD for construction costs, more than 50 m^2 of area, and roughly $700 USD for filter bag replacements and utilities per year. For wet scrubbers, the installation cost is approximately $2,000–7,000 USD, requires 10 m^2 area, and water costs, which are dependent on scrubbing intensity. This study suggests either option to be used as APCDs for Taiwanese temples.

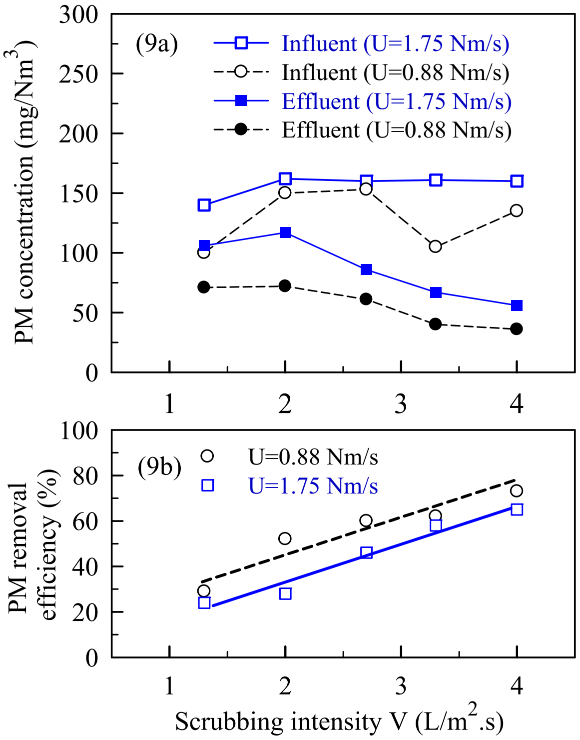

Fig. 9. Operation data of the scrubber: (9a) PM concentrations in the flue gas influent to and effluent from the scrubber, (9b) PM removal efficiency.

Table 5. Concentrations of CO_2, CO, and NO in gas at inlet and outlet of the wet scrubber and the removal efficiencies.

Compounds	Concentration		Removal efficiency (%)
	Inlet	Outlet	
CO_2 (%)	1.7–2.3	1.5–1.6	22.5
CO (ppm)	165–258	143–174	25.2
NO (ppm)	18–21	10–11	45.4

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