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Reducing Air Pollutant Emissions from Burning Incense with the Addition of Calcium Carbonate

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ABSTRACT

A laboratory-scale study was performed to quantify the pollutant reduction effects from burning incense with the addition of $CaCO_3$. Many studies have investigated the effects of burning incense on the quality of surrounding air, focusing primarily on particulate matter (PM) and polycyclic aromatic hydrocarbons (PAHs). However, the reduction of PM and PAHs from burning incense has received little attention. In our past study, we investigated nine types of commercially available incense and found that incense with a higher $CaCO_3$ content had lower PM and PAH emissions factors. Five to thirty percent of $CaCO_3$ was added to Liao and Chen incense powder, which are popular incense materials. The experimental results indicate that the reductions in the emissions of PM and PAHs from burning incense increased with along with amount of $CaCO_3$ additive. Mean PM reductions for 5.0%, 10.0%, 20.0%, and 30.0% $CaCO_3$ were 11 ± 2%, 15 ± 3%, 27 ± 1%, and 41 ± 3%, respectively. Mean particle-phase PAHs (P-PAHs) reductions were 9 ± 9%, 15 ± 5%, 22 ± 1%, and 28 ± 1%, respectively, and 5 ± 6%, 21 ± 1%, 21 ± 3%, and 30 ± 2% for total benzo[a]pyrene equivalent concentration (total BaP_{eq}), respectively. This study was performed to quantify the reduction of PM and PAH emissions from burning incense with increasing amounts of $CaCO_3$. The findings of this study may serve as a guide to producing safer and less-polluting incense.

Keywords: Incense; Calcium carbonate; Particulate matter; Polycyclic aromatic hydrocarbons; Total benzo[a]pyrene equivalent concentration.

INTRODUCTION

It was estimated that there were 11,796 legal temples in Taiwan in 2009. The temple density was roughly 1 temple per 2,000 residents or 1 temple per 260 hectares; these figures exclude unregistered temples and altars (Department of Statistics, MOI, 2010). Incense is burned in temples and widely used during temple activities in Asia. There are 6.1 million families in Taiwan, with 45% burning incense twice per day (Lung *et al.*, 2007). Cancer, asthma, dermatitis, and genotoxic effects are related to exposure to incense smoke (Dawod and Hussain, 1995; Yang *et al.*, 1997; Jetter *et al.*, 2002). Navasumrit *et al.* (2008) indicated that exposure to carcinogens emitted from incense burning may increase health risk for the development of cancer in temple workers. The burning of solid biomaterial such as incense, joss paper, tobacco, and wood has been demonstrated to significantly generate particulate matter (PM) (Fang *et al*., 2003; Choosong *et al*., 2010; Ning and Sioutas, 2010), polycyclic aromatic hydrocarbons (PAHs) (Yang *et al*., 2007; Lo *et al*., 2011), and polychlorinated dibenzo-*p*-dioxin/dibenzofurans (PCDD/Fs) (Wu *et al*., 2010; Chiu *et al*., 2011; Lin *et al*., 2011).

The PM emission factor from burning incense ranges from 41 to 54 mg/g with an average of 46 mg/g, which is higher than that for cigarettes (10 mg/g) (Löfroth *et al*., 1991; Mannix *et al*., 1996). Burning incense in an enclosed room results in a suspended particle concentration of 390–730 μg/m^3, which is 4–7 times higher than the indoor air particulate standard of the Taiwan EPA (100 μg/m^3) (Kao and Lung, 2000). Cheng *et al*. (1995) found that the count median diameter (CMD) and mass median aerodynamic diameter (MMAD) of smoke aerosol from incense burning in an enclosed chamber were 0.13 and 0.28 μm, respectively. In our previous study, it was found that the distribution profiles of P-PAHs are similar to those of particle sizes (Yang *et al*., 2007). Fine particles with diameters of less

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than 2.5 μm had higher specific surface areas and toxic effect than those of coarse particles with diameters of 2.5 μm to 10 μm. Moreover, small particles are more likely to harm the respiratory system as they can easily be inhaled and deposited in the respiratory tract and alveolar region (Harrison *et al*., 2000; USEPA, 2002; Voutsa and Samara, 2002). The efficiency of particle deposition in the respiratory tract is a function of the particle size (Pope *et al*., 1995; McAughey, 1997).

Several studies concluded that PAHs in indoor air mainly originated from incense burning in temples (Chiang and Liao, 2006; Lu *et al*., 2008). In our previous study, gas-phase PAH (G-PAH) and P-PAH emission factors ranged from 10 to 29 and 4.5 to 6.9 μg/g-incense, respectively. However, the particle-phase BaP_{eq} emission factor was found to be consistently more than 40-fold higher than that of the corresponding gas-phase BaP_{eq}. These results clearly suggest that in terms of carcinogenic potency, the control of P-PAH emissions is more important than the control of G-PAHs (Yang *et al*., 2007). Many studies have suggested that PAHs are environmental immunosuppressive contaminants. PAHs, especially benzo(a)pyrene, not only harm the respiratory and immune system but also cause cell mutation and cancer, including lung and skin cancer (Hecht, 1999; Knize *et al*., 1999; Laupeze *et al*., 2002; Page *et al*., 2002; Yousef *et al*., 2002; van Grevenynghe *et al*., 2003). Unfortunately, the reduction of PAHs and PM from burning incense has received little attention.

In our previous study, we investigated nine types of incense and found that incense with higher $CaCO_3$ content had lower PM and PAH emissions (Yang *et al*., 2006). However, there were variations in the proportion of bamboo, adhesive and wood flour in incense sticks, the size of powder, and the composition of individual additives due to manufacturing differences. All of these factors influence the characteristics of air pollution from burning incense. Therefore, the incense used in the present study was made in our laboratory. In order to control the variations of incense characteristics, we added $CaCO_3$ and identified the reduction of PM and PAHs emissions in burning incense. The findings of this study are useful for safer and less-polluting incense produced.

METHODS

Manufacture of Test Incense

The main components of incense are powder and stick. Incense powders used in this study contains three ingredients including wood flour, adhesive (Machilus kusanoi Hay, a species of *Lauraceae*) and additives. Incense stick here is a bamboo stick (Phyllostachys makinoi Hay) which is a general specification of incense manufacturers (length: 39.5 cm, weight: 0.55 g). Incense is named after its wooden materials; popular incense includes Liao and Chen. Liao incense is made from Chinese medical herbs. Chen incense was made from the several years' accumulation of natural resin which is caused by germs when the wood (A. malaccensis, a genus of *Aquilaria*) is hurt. The incense was partially handmade to reduce experimental error and to keep the process consistent. Each batch of incense used 100 g of powder. The proportion of adhesive in the powder was 20.0% (20.0 g). Besides, the percentages by weight of $CaCO_3$ in the powder were 5.0% (5.0 g), 10.0% (10.0 g), 20% (20.0 g), and 30% (30.0 g). The powder was then mixed with 100 g of deionized water. Aquiferous powder was pressed onto the bamboo stick with a hydraulic press machine to make semi-finished incense. The finished samples were conditioned in a carriage at 25°C under a relative humidity of 50% for 24 hrs before being weighed. The weights of the samples were 1.00 ± 0.02 g. The schematic diagram of test incense stick is illustrated in Fig. 1. Each incense stick base part was 11.5 cm, 0.16 g of bamboo, burned part was 28 cm, 0.84 g, including 0.45 g of powder (adhesive 0.09 g) and 0.39 g of bamboo. The detailed compositions of the test incense with various amounts of $CaCO_3$ additive are listed in Table 1.

Sampling Program

The sampling set-up is illustrated in Fig. 2 (Yang *et al*., 2006). The air exchange rate (Ach) in a domestic environment in Taiwan ranges from 0.8 to 3.5 Ach in summer and 0.5 to 2.0 Ach in winter (Li and Ro, 2000). In this study, the air exchange rate was maintained at 1.5 Ach to simulate natural adequate ventilation conditions. All experiments were conducted in a 1.2-m^3 stainless steel #304 environmental test chamber with a 30 L air/min flow rate. An air-cleaning train, consisting of a high-efficiency particulate air (HEPA) filter set, followed immediately by an activated carbon bed and a XAD-2 resin bed, was used to provide clean air. The train sequentially removed particulates, gaseous components, and organic substances in the feed air before it was drawn into the combustion chamber. Before each run, the chamber was first flushed thoroughly with clean air provided by the above-mentioned system. In order to prevent the air from directly blowing on the burning incense, the air was forced to pass through packing rings before entering the combustion room. Finally, the outlet air was pumped out of the laboratory. A panel-mounted flow meter was installed in front of a 187-W (1/4-hp) air pump. To avoid possible errors in flow measurement, the panel-mounted flow meter was recalibrated with an infrared ray soap bubble calibrator (Gilibrator-2, Gilian Instrument Corp.) after every 5−7 runs. A small low-speed fan was placed inside the chamber, which blew towards

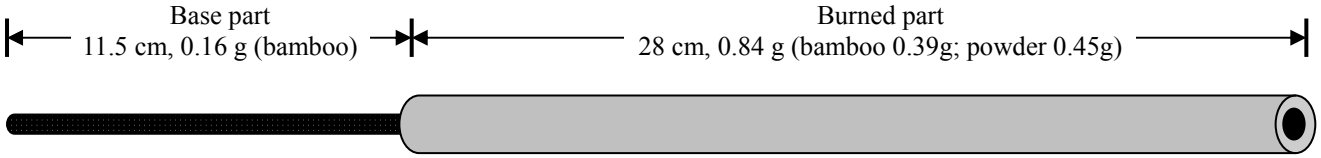

Fig. 1. Schematic diagram of test incense stick.

Table 1. Composition of test incense stick for various amounts of $CaCO_3$ additive.

Test incense[a]	$CaCO_3$ in powder (%)	Powder (g) = 0.45 g			Bamboo (g)[b]
		$CaCO_3$	Wood flour	Adhesive	
CC00	0	0	0.36	0.09	0.55
CC05	5.0	0.0225	0.4275	0.09	0.55
CC10	10.0	0.045	0.405	0.09	0.55
CC20	20.0	0.09	0.36	0.09	0.55
CC30	30.0	0.135	0.315	0.09	0.55

a: the weight of one stick of all types of test incense was 1.00 g (0.45 g powder and 0.55 g bamboo stick).
b: the weight of each stick bamboo burned was 0.39 g.

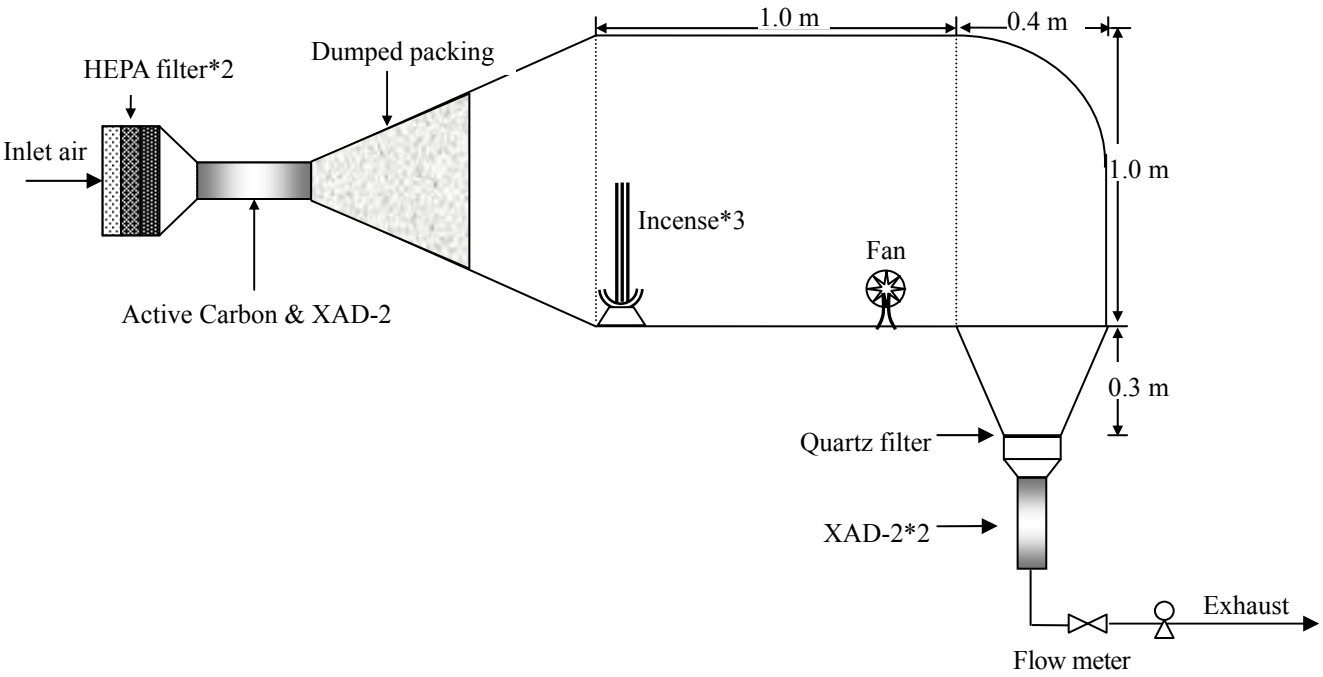

Fig. 2. Schematic diagram of the burning chamber with sampling attachments.

a corner of the ceiling of the chamber (away from the incense) to stir the air without directly affecting the rising plume of smoke. This study monitored the temperature maintained below 35°C during sampling in the chamber. We set up replicated tests for 10 types of incense and each of them was performed six times.

Incense sticks (three sticks per run) were placed upright on a pre-weighed metallic plate. A ring stand held the samples in the rear of the chamber. At the beginning of each run, the incense sticks were positioned so that their tips were located roughly at the half-height of the chamber. The incense sticks were briefly lit with a propane lighter. The flame was then immediately put out to initiate smoldering. To ensure quantitative collection of all smoke generated during each run, clean air (pumped at a flow rate four times that used for incense burning) was continuously drawn to purge the chamber for four additional hours after the combustion was completed.

The quartz filters (Gelman Series, 100 mm in diameter) were pretreated before sampling by heating in a muffle furnace in air for 2.5 h at 900°C. Each quartz filter was cleaned by extraction with a mixed solvent (1:1 n-hexane and dichloromethane) for 24 hrs in a Soxhlet extractor. The filters were conditioned for 24 hrs at constant 25°C and a relative humidity of 50% in a dry box before and after sampling.

Analyses of PAHs

After final weighing, all filters were separately placed in appropriate Soxhlet extractors and extracted with 600 mL of a dichloromethane /n-hexane mixture (v/v = 1:1) for 24 hrs. The extract was then concentrated under ultra-pure nitrogen, cleaned, and re-concentrated to exactly 1.0 mL. All extracts were analyzed with a gas chromatograph/mass selective detector (GC/MSD) (GC-6890N with MSD-5973, Agilent Technologies, USA) with a J&W Ultra2 capillary column (50 m × 0.314 mm × 0.17 μm). A computer-controlled automatic sampler (Model 3365, Hewlett Packard, USA) was used in conjunction with the GC/MSD system. All injections were splitless with an injection volume of 1 μL. The injector and the detector temperatures were 300 and 325°C, respectively. The temperature program included an immediate fast initial increase from 50 to 100°C at 20 °C/min, followed by a milder increase from 100 to 290°C at 3 °C/min, and finally a hold at 290°C for 20 minutes.

The concentrations of the following PAHs were determined: naphthalene (Nap) for 2-ring; acenaphthylene (AcPy), acenaphthene (Acp), fluorene (Flu), phenanthrene (PA), and anthracene (Ant) for 3-ring; fluoranthene (FL), pyrene(Pyr), benzo[*a*]anthracene (BaA), and chrysene (CHR) for 4-ring; benzo[*b*]fluoranthene (BbF), benzo[*k*]fluoranthene (BkF), benzo(*a*)pyrene (B*a*P), dibenzo[*a,h*]anthracene (DBA) for 5-ring; and indeno[1,2,3,-*cd*]pyrene (IND), benzo[*ghi*]perylene (Bghip) for 6-ring.

The GC/MSD was calibrated with a diluted standard solution of 16 PAH compounds (PAHs mixture-610M from Supelco). The standard solution concentrations were 0.001, 0.005, 0.01, 0.05, 0.1, 0.5, 1, 5 and 10 μg/mL. PAHs recovery efficiencies were determined by processing a solution containing known PAHs concentrations through the same experimental procedure used for the samples. The recovery efficiencies of PAHs varied from 69.1 (Nap) to 98.3 (BaA), with an average of 87.6%. The method detection limit (MDL) for the 16 PAHs, including Nap, Acpy, Acp, Flu, Pa, Ant, Fl, Pyr, BaA, CHR, BbF, BkF, BaP, IND, DBA and BghiP, were found to be 0.560, 0.531, 0.430, 0.623, 0.832, 0.071, 0.319, 0.098, 0.244, 0.542, 0.405, 0.274, 0.542, 0.273, 0.936, and 0.443 ppb, respectively. Ten consecutive injections of a PAHs 610-M standard yielded an average relative standard deviation (RSD) of the GC integration area of 3.0%, with a range of 0.8–5.1%. The blank tests for PAHs were accomplished using the same procedure as that used for the recovery-efficiency tests without adding the known standard solution before extraction. Analyses of field blanks, including the blank quartz filter and glass bottle showed no significant contamination (GC/ MSD integrated area < detection limit). The calculation procedures of the incense PAH results were not modified with the recovery efficiencies and the field blanks. The recovery efficiencies of the 16 individual PAH compounds and the field blanks were not used to modified the PAH results.

Data Analysis

The 16 individual PAHs were divided according to their molecular weight into three categories: low molecular weight (LM–PAHs containing two- and three-ringed PAHs); middle molecular weight (MM–PAHs containing four-ringed PAHs); and high molecular weight (HM–PAHs containing five- and six-ringed PAHs). The total PAHs concentration was the sum of the concentrations for the 16 PAH compounds in each collected sample. Moreover, considering that several PAH compounds are known human carcinogens, the carcinogenic potencies of PAHs emissions from each emission source were also determined. In principle, the carcinogenic potency of a given PAH compound is assessed on the basis of its BaP_{eq}. The calculation of the BaP_{eq} concentration for a given PAH compound is determined by its toxic equivalent factor (TEF), which represents the relative carcinogenic potency of the given PAH compound, using benzo[a]pyrene as a reference compound to adjust its original concentration. This study applied the TEFs completed by Nisbet and LaGoy (1992) to asses the carcinogenic potency of total PAHs (i.e., total BaP_{eq}) using the sum of the BaP_{eq} concentrations estimated for each PAH compound with a TEF in the total PAHs.

RESULTS AND DISCUSSION

Burning Time and Burning Rate of Test Incense

The effect of $CaCO_3$ additive on the burning time and burning rate of the test incense, Liao incense and Chen incense, is shown in Table 2. For Liao incense, the mean reductions of burning time for CC05, CC10, CC20, and CC30 $CaCO_3$ additives were 4.3 ± 3.2%, 8.5 ± 3.2%, 22 ± 3.2%, and 30 ± 3.2%, respectively. For Chen incense, the mean reductions were 5.7 ± 5.7%, 9.2 ± 6.9%, 24 ± 3.4%, and 39 ± 3.4%, respectively. The mean reductions of burning time were 5.0 ± 1.1%, 8.9 ± 0.5%, 23 ± 1.3%, and 34 ± 6.6%, respectively, for CC05, CC10, CC20, and CC30. In this study, we controlled the process variations and added accurate amounts of $CaCO_3$ to help verify the reduction of burning time. The mean burning time of the two types for CC30 incense was less than 60 minutes. Users prefer incense with a long burning time. The appropriate burning time was important. The results can be applied to the commercial production of incense.

These results may be attributed to $CaCO_3$, which has a high boiling point; $CaCO_3$ may trap the heat energy generated at the burning tip during combustion. Moreover, $CaCO_3$ with refractory characteristics in terms of low heat transfer coefficient (0.05 W/mol·k) and high molar heat capacity (81.88 J/mol·K) will prevent air convection and thus raise the burning rate of inflammable substances. Compared with the result conducted by Yang (Yang *et al*, 2006), the reasons for high burning rate observed in this study included different raw materials, smaller diameter incense (2.2 mm in this study, 2.5–3.0 mm in previous study), incense density changes resulted from incense production (semi-handmade in this study, machine-made in previous study).

PM Emission Factor

The PM emission factor results are shown in Fig. 3. It was

Table 2. Burning time and burning rate of test incense for various amounts of $CaCO_3$ additive.

Test incense	$CaCO_3$ in burned part (%)	Burning time (min)		Burning rate (mg/min)	
		Liao	Chen	Liao	Chen
CC00	0	94 ± 1	87 ± 2	27 ± 1	29 ± 1
CC05	2.68	90 ± 2	82 ± 3	27 ± 1	31 ± 1
CC10	5.36	86 ± 2	79 ± 4	29 ± 0	32 ± 2
CC20	10.7	73 ± 2	66 ± 1	35 ± 1	38 ± 0
CC30	16.1	66 ± 2	53 ± 1	38 ± 1	47 ± 1

N = 6 for each type of incense.

found that the PM emission factor values of original (CC00) Liao incense and Chen incense were 31 ± 2.1 and 40 ± 1.4 mg/g-incense, respectively. For Liao incense, the mean PM reductions for CC05, CC10, CC20, and CC30 were 10 ± 14%, 13 ± 12%, 26 ± 14%, and 39 ± 11%, respectively. For Chen incense, the mean reductions were 13 ± 7.0%, 18 ± 10%, 28 ± 8.3%, and 43 ± 5.5%, respectively. These results indicate that the reduction of PM emissions increases with increasing amount of $CaCO_3$ additive.

The correlations of the PM emission factor and the $CaCO_3$ in powder with regression analysis ($r^2 = 0.99$, $p < 0.01$ for Liao; $r^2 = 0.98$, $p < 0.01$ for Chen) were strongly negative. Thus, the more addition of $CaCO_3$ in powder will emitted less the particulate emissions in burning incense. Moreover, the mean PM reductions for the two types of test incense were 11 ± 2%, 15 ± 3%, 27 ± 1%, and 41 ± 3%, respectively, for CC05, CC10, CC20, and CC30, which are higher than the $CaCO_3$ content was 2.68%, 5.36%, 10.7%, and 16.1% in the burned part, respectively. These results indicate that the addition of $CaCO_3$ significantly reduces PM emissions. This may be attributed to $CaCO_3$, which acted as noncombustible replacer to reduce emission from organic wood material, such as bamboo, adhesive, and wood flour in the burned incense.

PAH Emission Factor

The emission factor results of P-PAHs are shown in Fig. 4. It was found that the P-PAHs emission factors for original Liao incense and Chen incense were 7.9 ± 0.7 and 7.5 ± 0.5 μg/g-incense, respectively. For Liao incense, the mean P-PAHs reductions for CC05, CC10, CC20, and CC30 were 3 ± 20%, 12 ± 14%, 23 ± 11%, and 27 ± 16%, respectively. For Chen incense, the mean reductions were 15 ± 8.0%, 18 ± 9.1%, 21 ± 13%, and 29 ± 12%, respectively. Similar results were found for total BaP_{eq}. The emission factor results of total BaP_{eq} are shown in Fig. 5. The total BaP_{eq} emission factor values for original Liao incense and Chen incense

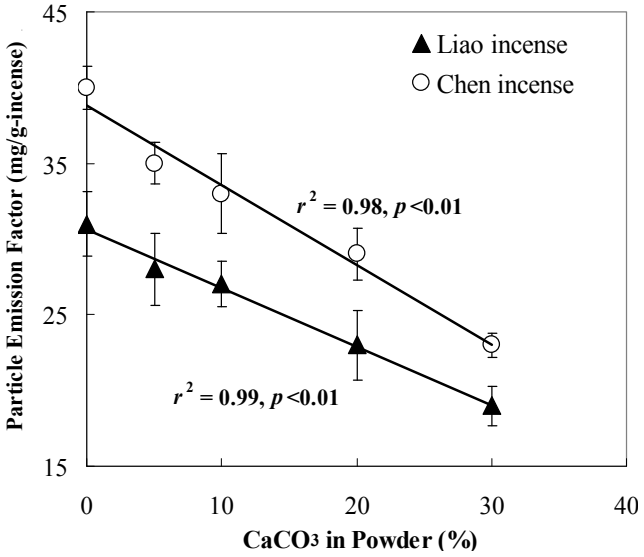

Fig. 3. PM emission factor of test incense for various amounts of $CaCO_3$ additive (Each error value equals one standard deviation)

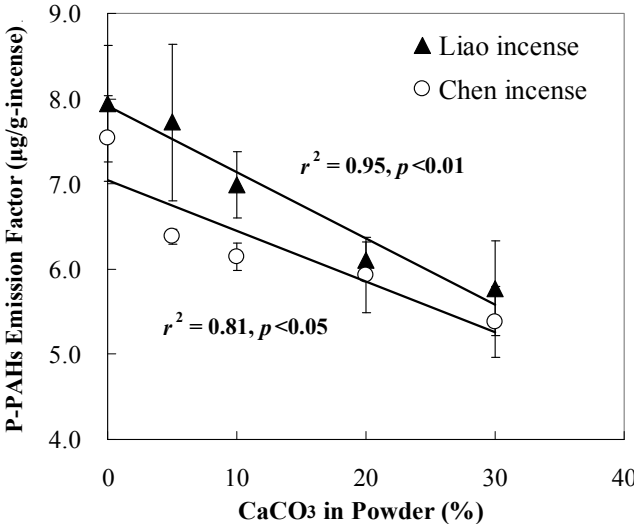

Fig. 4. P-PAH emission factor of test incense for various amounts of $CaCO_3$ additive (Each error value equals one standard deviation).

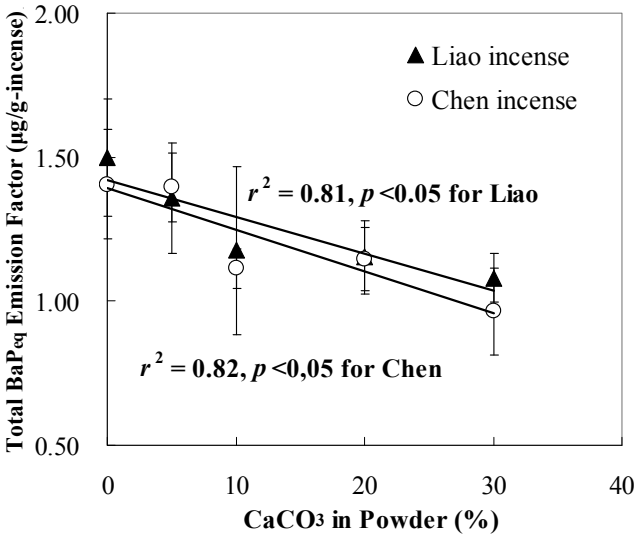

Fig. 5. Total BaP_{eq} emission factor of test incense for various amounts of $CaCO_3$ additive (Each error value equals one standard deviation).

were 1.5 ± 0.2 and 1.4 ± 0.2 μg/g-incense, respectively. For Liao incense, the mean total BaP_{eq} reductions for CC05, CC10, CC20, and CC30 were 9 ± 22%, 22 ± 31%, 23 ± 19%, and 28 ± 17%, respectively. For Chen incense, the mean reductions were 1 ± 22%, 21 ± 19%, 18 ± 21%, and 31 ± 24%, respectively. These results indicate that P-PAHs and total BaP_{eq} emissions from incense can be reduced using $CaCO_3$ additive; the reduction increased with increasing amount of $CaCO_3$ additive.

The correlations of the P-PAHs emission factor and the $CaCO_3$ in powder with regression analysis ($r^2 = 0.95$, $p < 0.01$ for Liao; $r^2 = 0.81$, $p < 0.05$ for Chen) were strongly negative. In addition, the correlations of the total BaP_{eq} emission factor and the $CaCO_3$ in powder with regression analysis ($r^2 = 0.81$, $p < 0.05$ for Liao; $r^2 = 0.82$, $p < 0.05$ for

Chen) were strongly negative. Thus, the more addition of $CaCO_3$ in powder will emitted less the P-PAHs and total BaP_{eq} emissions in burning incense.

As mentioned, $CaCO_3$ content was 2.68%, 5.36%, 10.7%, and 16.1% in the burned part, respectively, for CC05, CC10, CC20, and CC30, which are less than the means of P-PAHs reductions (9 ± 9%, 15 ± 5%, 22 ± 1%, and 28 ± 1%, respectively) and total BaP_{eq} reductions (5 ± 6%, 21 ± 1%, 21 ± 3%, and 30 ± 2%, respectively) for the two types of test incense. These results strongly suggest that the addition of $CaCO_3$ significantly reduces P-PAHs emissions. These results may be attributed to $CaCO_3$ decreased the smolder effect during incense combustion. Therefore, the addition of $CaCO_3$ efficiently decreases genotoxic P-PAHs.

Profiles of PAHs

The 16 individual PAHs were divided according to their molecular weight into three categories: LM-PAHs, MM-PAHs and, HM-PAHs. Table 3 and Fig. 6 show that the emission factor values for Liao incense were 0.97 ± 0.31,

Table 3. Individual 16 P-PAH emission factors of test incense for various amounts of $CaCO_3$ additive.

P-PAHs	Liao incense					Chen incense				
(μg/g-incense)	CC00	CC05	CC10	CC20	CC30	CC00	CC05	CC10	CC20	CC30
Nap	0.11 ± 0.04	0.09 ± 0.06	0.09 ± 0.06	0.05 ± 0.04	0.05 ± 0.03	0.15 ± 0.04	0.02 ± 0.07	0.09 ± 0.05	0.08 ± 0.03	0.03 ± 0.04
Acpy	0.12 ± 0.06	0.11 ± 0.04	0.27 ± 0.10	0.10 ± 0.04	0.09 ± 0.03	0.30 ± 0.08	0.03 ± 0.23	0.21 ± 0.11	0.08 ± 0.05	0.02 ± 0.04
Acp	0.02 ± 0.02	0.02 ± 0.01	0.03 ± 0.01	0.01 ± 0.03	0.01 ± 0.02	0.03 ± 0.00	0.01 ± 0.01	0.03 ± 0.00	0.02 ± 0.03	0.01 ± 0.01
Flu	0.04 ± 0.01	0.03 ± 0.05	0.04 ± 0.03	0.03 ± 0.04	0.03 ± 0.05	0.04 ± 0.02	0.02 ± 0.02	0.04 ± 0.01	0.03 ± 0.01	0.01 ± 0.03
Pa	0.49 ± 0.21	0.55 ± 0.32	0.68 ± 0.33	0.42 ± 0.26	0.39 ± 0.37	0.65 ± 0.17	0.32 ± 0.22	0.56 ± 0.25	0.36 ± 0.21	0.16 ± 0.17
Ant	0.19 ± 0.03	0.32 ± 0.05	0.26 ± 0.02	0.16 ± 0.06	0.20 ± 0.05	0.29 ± 0.01	0.13 ± 0.03	0.20 ± 0.02	0.15 ± 0.05	0.04 ± 0.02
Fl	0.63 ± 0.26	0.64 ± 0.34	0.64 ± 0.22	0.60 ± 0.32	0.47 ± 0.13	0.61 ± 0.19	0.49 ± 0.23	0.51 ± 0.18	0.46 ± 0.21	0.41 ± 0.18
Pyr	0.67 ± 0.10	0.68 ± 0.08	0.62 ± 0.10	0.62 ± 0.14	0.50 ± 0.09	0.61 ± 0.08	0.53 ± 0.03	0.50 ± 0.07	0.47 ± 0.08	0.42 ± 0.06
BaA	0.81 ± 0.31	0.73 ± 0.18	0.64 ± 0.21	0.82 ± 0.37	0.53 ± 0.19	0.65 ± 0.32	0.65 ± 0.29	0.59 ± 0.16	0.57 ± 0.26	0.57 ± 0.22
CHR	1.33 ± 0.47	1.17 ± 0.52	1.10 ± 0.34	0.86 ± 0.35	0.86 ± 0.31	1.00 ± 0.41	1.04 ± 0.41	0.99 ± 0.42	0.98 ± 0.46	1.01 ± 0.37
BbF	0.54 ± 0.16	0.48 ± 0.12	0.46 ± 0.13	0.41 ± 0.11	0.37 ± 0.08	0.52 ± 0.07	0.54 ± 0.17	0.40 ± 0.12	0.47 ± 0.12	0.51 ± 0.10
BkF	0.34 ± 0.08	0.43 ± 0.06	0.22 ± 0.03	0.22 ± 0.02	0.26 ± 0.04	0.39 ± 0.04	0.27 ± 0.08	0.19 ± 0.03	0.28 ± 0.02	0.28 ± 0.03
BaP	1.11 ± 0.25	1.00 ± 0.22	0.82 ± 0.17	0.84 ± 0.31	0.80 ± 0.22	0.97 ± 0.38	1.05 ± 0.43	0.81 ± 0.33	0.84 ± 0.27	0.64 ± 0.38
IND	0.71 ± 0.15	0.67 ± 0.14	0.51 ± 0.06	0.50 ± 0.06	0.55 ± 0.11	0.59 ± 0.12	0.61 ± 0.06	0.49 ± 0.13	0.57 ± 0.06	0.62 ± 0.12
DBA	0.13 ± 0.06	0.10 ± 0.08	0.15 ± 0.09	0.10 ± 0.07	0.09 ± 0.07	0.19 ± 0.07	0.12 ± 0.10	0.12 ± 0.06	0.10 ± 0.09	0.11 ± 0.07
BghiP	0.70 ± 0.18	0.69 ± 0.15	0.44 ± 0.09	0.35 ± 0.11	0.56 ± 0.18	0.53 ± 0.18	0.58 ± 0.14	0.40 ± 0.20	0.50 ± 0.14	0.55 ± 0.13
ΣLM-PAHs	0.97 ± 0.31	1.12 ± 0.28	1.37 ± 0.42	0.77 ± 0.19	0.77 ± 0.21	1.46 ± 0.17	0.53 ± 0.24	1.13 ± 0.22	0.71 ± 0.28	0.27 ± 0.12
ΣMM-PAHs	3.44 ± 0.52	3.22 ± 0.54	3.00 ± 0.67	2.90 ± 0.46	2.36 ± 0.38	2.87 ± 0.66	2.71 ± 0.49	2.59 ± 0.31	2.47 ± 0.41	2.41 ± 0.34
ΣHM-PAHs	3.53 ± 0.47	3.37 ± 0.41	2.60 ± 0.18	2.42 ± 0.18	2.63 ± 0.36	3.19 ± 0.39	3.17 ± 0.21	2.41 ± 0.33	2.75 ± 0.27	2.71 ± 0.25
Total PAHs	7.94 ± 0.68	7.72 ± 0.92	6.99 ± 0.39	6.10 ± 0.22	5.78 ± 0.55	7.53 ± 0.51	6.38 ± 0.09	6.14 ± 0.17	5.93 ± 0.44	5.38 ± 0.41

Note: P-PAHs: Particle-phase PAHs.
LM-PAHs: Low Molecular Weight PAHs (2-3ring).
MM-PAHs: Median Molecular Weight PAHs (4rings).
HM-PAHs: High Molecular Weight PAHs (5-6rings).

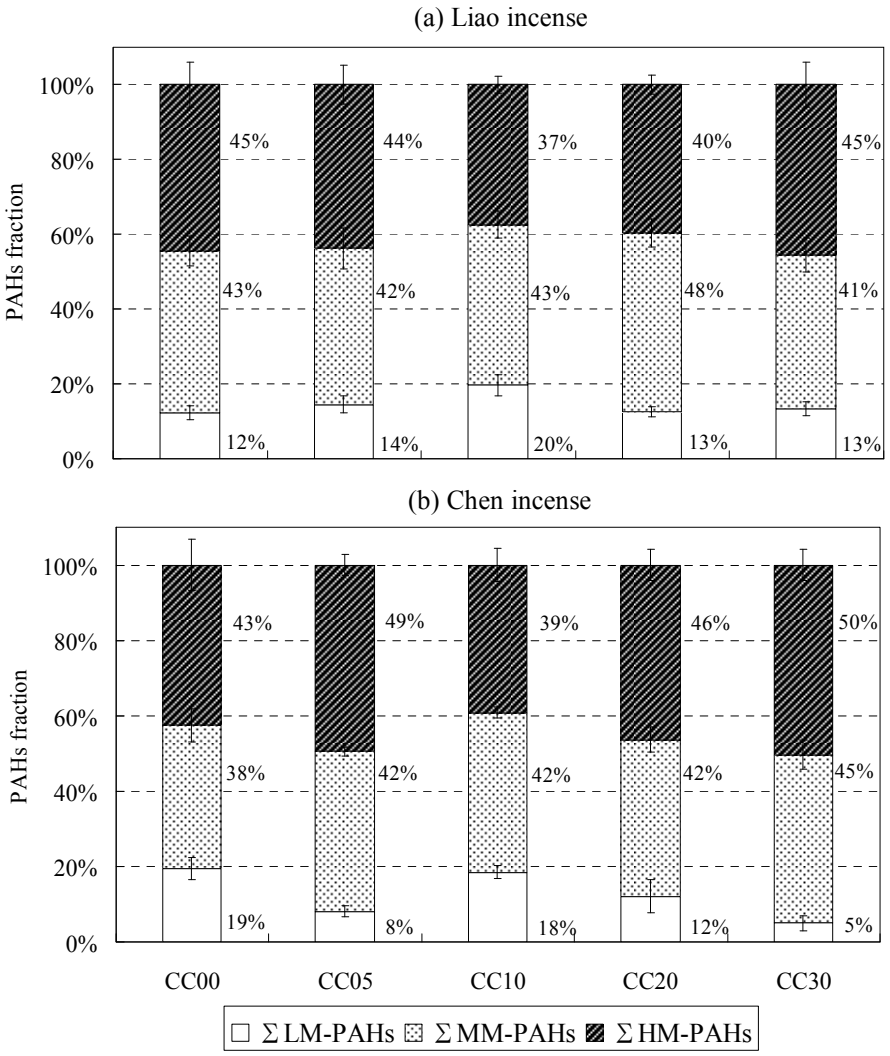

Fig. 6. Fractions of P-PAH classifications of test incense for various amounts of $CaCO_3$ additive: (a) Liao incense; (b) Chen incense.

3.44 ± 0.52, and 3.53 ± 0.47 μg/g-incense, respectively, accounting for 12 ± 3.9%, 43 ± 6.6%, and 45 ± 5.9% of total P-PAHs. LM-PAH, MM-PAH, and HM-PAH emission factor values from Liao incense for CC05, CC10, CC20, and CC30 were 0.77–1.37, 2.36–3.22, and 2.42–3.37 μg/g-incense, respectively, accounting for 13–20%, 41–48%, and 37–45% of total P-PAHs. For Chen incense, the values were 1.46, 2.87, and 3.19 μg/g-incense, respectively, accounting for 19 ± 2.9%, 38 ± 11%, and 43 ± 6.8% of total P-PAHs. For Chen incense, the values were 0.27–1.13, 2.41–2.71, and 2.41–3.17 μg/g-incense, respectively, accounting for 5.0–18%, 42–45%, and 39–50% of total P-PAHs.

In addition, according to Chi-Square test of homogeneity, the percentages of the rings of PAHs were quite similar to those of ten types of incense ($p > 0.5$). On the other words, the PAHs emission profiles of the two original types of incense are similar. In addition, it may be concluded that individual PAH emission profiles of various types of incense are similar and thus independent of $CaCO_3$ content. The reason might be that although the incense with $CaCO_3$ burned less organic material, it was still a wood combustion type.

CONCLUSIONS

Experimental results indicate that the addition of 10% $CaCO_3$ in powder reduced the burning time by 10 ± 1.2 min, increased the burning rate by 5.0 ± 1.2 mg/min, reduced PM by 4.56 ± 0.99 mg/g-incense, and reduced P-PAHs by 0.75 ± 0.08 μg/g-incense and particle phase BaP_{eq} by 0.15 ± 0.01 μg/g-incense with linear regression analysis. Summary of above-mentioned, these results may be attributed to a lower amount of organic wood materials, such as bamboo, adhesive, and wood flour, being burned in incense with $CaCO_3$ additives. $CaCO_3$ prevented air convection and kept a high temperature at the burning tip, which decreased the smolder effect during incense combustion. In addition, individual PAH emission profiles of various types of incense are similar and thus independent of $CaCO_3$ content. However, the quality of incense, in terms of fragrance emission rate and burning time, may be slightly compromised due to enhanced burning efficiency, the addition of $CaCO_3$ effectively reduces emissions that are harmful to human health. The findings of this study may serve as a guide for producing safer incense.

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