Journal of Hazardous Materials 140 (2007) 165–172

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Burning characteristics and emission products related to metallic content in incense

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Received 1 July 2005; received in revised form 12 April 2006; accepted 19 June 2006
Available online 21 June 2006

Abstract

This study mainly compared particulate emission factors of nine popular incense. The influence of metallic contents upon the burning rate, ash and particulate emission factors of combustion was discussed. The contents of Ca and K were the highest among all metallic elements in the raw materials of the incense (the geometric mean contents 8.7 and 2.5 mg g^{-1}, respectively), followed by Al, Mg, Fe, Na (0.1–1.0 mg g^{-1}) and Ba, then Sr, Mn, Cu and Zn (<0.01–0.1 mg g^{-1}). Most calcium existed as inorganic salts, such as $CaCO_3$. Under the same burning conditions, the particulate generation rates are similar (0.50 mg min^{-1} ± 9%) among different types of incense—the shorter the combustion duration of a stick, the lower the total suspended particulate emission. Additionally, with the same incense weight burned, the greater the emission of ash is, the lower the emission of suspended particulate. It is recommended that consumers select incense which produces more ash, hence less particulate, to minimize the threat to their' health. Additionally, when the total metallic content (with Ca as the major component) was lower than 2% of the raw materials, properly increasing the total metallic content (from 0.5 to 2.0%) can effectively reduce the level of particulates (about 40%) during the combustion.

Keywords: Incense; Combustion duration; Burning rate; Emission factor; Generation rate

1. Introduction

Worshipping ancestors and gods by burning incense sticks is a very important custom in Taiwanese and Chinese culture. However, incense burning causes air pollution, which may pose some health risks, especially when the room is poorly ventilated.

In the indoor environment, smoking and cooking are known to be significant particle sources [1]. However, incense burning also contributes significantly to indoor particle concentrations in oriental countries [2,3]. In Kao's study [4], burning incense in an enclosed room resulted a suspended particle concentration of 390–730 μg m^{-3}, which is 4–7 times higher than indoor air particulate standard in Taiwan EPA (100 μg m^{-3}). Burning incense was found to generate large quantities of particulates (an average of above 45 mg g^{-1} burned, as opposed to those of the side stream about 10 mg g^{-1} burned for the cigarettes) [5]. Lung and Hu [6] studied burning of Chih-Chen incense sticks (two types) inside a 44 cm long and 4.7 cm diameter elutriator and found that each gram of incense emitted about 19.8–43.6 mg of particulate matter and 17.1–25.2 μg of S-PAHs.

Smoke from incense is known to contain PAHs and aromatic aldehydes. Using the Ames test, incense burning has been found to generate carcinogenic compounds [7]. Thus, Min et al. [8] suggests that burning incense might be explained why many Chinese people develop nasopharyngeal carcinoma.

At the Tzu Yun Yen temple sampling site in Taiwan, elements Fe, Zn, and Pb are the three major compositions for the two incense types. The metallic element concentration order for these elements is Fe > Zn > Cr > Cd > Pb > Mn > Ni > Cu in fine particles ($PM_{2.5}$) and Fe > Zn > Cr > Pb > Cd > Ni > Mn > Cu in coarse particles ($PM_{2.5–10}$) [9].

The principal metallic components in wood ashes are calcium, potassium and magnesium. The most common acidic

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doi:10.1016/j.jhazmat.2006.06.052

radicals are $–CO_3$, $–PO_4$, and $–SO_3$. Additionally, small amounts of sodium, manganese, aluminum, iron, sulfates and chlorides are almost invariably found in wood ashes [10].

Additionally, certain metallic elements in the materials are essential for combustion. As Yeh's study [11] has indicated, alkali metal ions such as K and Na function as the enhancer in the combustion and smoldering combustion of cotton fabrics.

The critical factors in cellulose fabrics for burning are the potassium and/or sodium ion content and the thermal fabric characteristics. Additionally, for fabrics with potassium and sodium ion contents in the range of approximately 1500–2500 ppm, the sensitivity to environmental factors increased [12]. Byung et al. [13] found that cellulose with NaCl shows a high laevoglucose burning decomposition rate, and a fast conversion rate of heavy initial products to CO_2.

Inorganic additives are classified according to their ability to enhance or inhibit smoldering combustion in cotton fabric. Thermal analysis shows that the oxidation rate of chars produced by pyrolysis of fabric treated with smolder-enhancing metal salts is higher than that of chars from fabric treated with additives such as phosphates and boric acid, which prevent smoldering [14]. NaCl, a smoldering combustion enhancer, slightly stabilizes pyrolysis of cellulose [15].

The sizes of suspended particulate emitted from burning incense were approximately 130–280 nm [16], meaning these particulate can easily enter the pulmonary alveoli of the human respiratory system. An additional concern is that many compounds found in the incense smoke are known to be mutagenic and pose serious threat to human's health [17].

Previous studies have so far only discussed the characteristics of pollutants induced by incense burning. The relationship between the material contents of incense and the emitted air pollutants is seldom mentioned. In this study, incense smoke and ash were analyzed in a condition of no interference. The relationship between the metallic contents and combustion characteristics (burning rate, particulate emission factor and ash emission factor) are discussed herein. The results of the study can help incense manufacturers improve their materials and reduce air pollutants. Moreover, the results can help consumers select less health-damaging incense.

2. Materials and methods

2.1. Selection of incense stick

The main material of incense are incense powder, bamboo sticks and natural adhesive. The incense powder is made of pulverized powder of different woods. Incense are named after their wooden materials, including Gui, Liao, Hsing Shan, Lao Shan and Chen. The bamboo stick, which functions as the mainstay of the incense, accounts for approximately 30% of the total weight of the incense. Finally, the adhesive is made of the bark of Machilus Kusanoi Hay (a species of Lauraceae), which becomes sticky when mixed with water. The adhesive takes approximately 10% (w/w) of the total weight of the incense. During manufacturing, the bamboo stick is first immersed in water. The wetted bamboo is then repeatedly coated with layers of adhesive and incense powder. Additionally, manufacturers may add various spices and inorganic salts to provide different fragrances or to lower the cost. According to market surveys and factory visits, the most commonly used inorganic salt is calcium carbonate.

This study selected nine incense from the five wooden materials mentioned above, whose physical characteristics are shown in Table 1. The sticks and the holding parts of the nine different incense are similar. The diameters of the holding parts are the same, while those of combustible parts are different. The weights of the incense sticks are also different.

2.2. Sampling

Fig. 1 shows the sampling configuration. Li and Ro [3] reported that the average air exchange rates of domestic environments in Taiwan were around 0.8–3.5 Ach (air changes per hour) in summer and 0.5–2.0 Ach in winter. In this study, the air exchange rate was maintained at 1.5 Ach to simulate normal natural ventilation. The controlled experiments were conducted in a 1.2 m^3 stainless steel #304 environmental test chamber with a flow rate of 30 l min^{-1}.

Before sampling, the chamber was first purged with blower air, which was passed through a clean air system. High-Efficiency Particulate Air (HEPA) filters followed by activated carbon and XAD-2 provided clean air for the experiments. To

Table 1
Physical characteristics of nine types of incense sticks

Incense	General name	Whole stick		Combustible part	
		Length (cm)	Weight (g)	Length (cm)	Diameter (mm)
A	Gui 1	39.4 ± 0.08	1.74 ± 0.21	29.0 ± 0.11	3.0 ± 0.3
B	Liao 1	39.2 ± 0.09	1.10 ± 0.07	28.8 ± 0.10	2.5 ± 0.1
C	Liao 2	39.3 ± 0.08	1.41 ± 0.04	28.9 ± 0.15	2.8 ± 0.1
D	Hsing Shan 1	39.5 ± 0.09	1.40 ± 0.04	28.2 ± 0.12	2.7 ± 0.0
E	Hsing Shan 2	39.2 ± 0.07	1.17 ± 0.10	28.5 ± 0.12	2.6 ± 0.2
F	Lao Shan 1	39.3 ± 0.08	1.35 ± 0.05	28.0 ± 0.11	2.8 ± 0.1
G	Lao Shan 2	39.2 ± 0.08	1.24 ± 0.05	27.9 ± 0.10	2.6 ± 0.2
H	Chen 1	39.3 ± 0.07	1.17 ± 0.04	28.6 ± 0.14	2.6 ± 0.0
I	Chen 2	39.2 ± 0.09	1.14 ± 0.05	28.9 ± 0.14	2.5 ± 0.1

$N = 6$ for each type of incense.

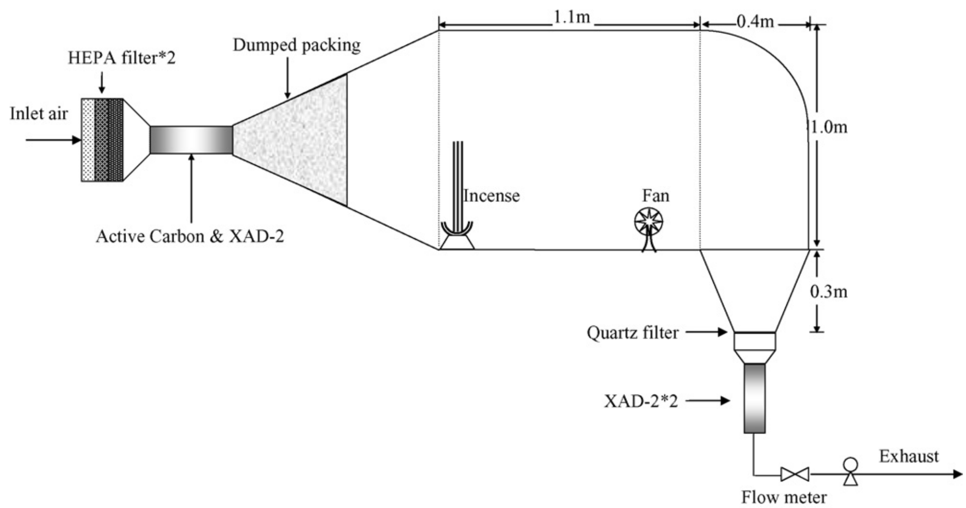

Fig. 1. Schematic diagram of simulation burning chamber with sampling attachments.

prevent the air from blowing the burning incense directly, the gas flow passed through the dumped packing before entering the combustion room. Finally, the outlet air was pumped out of the laboratory.

A panel-mounted flow meter was installed before a 1/4-hp air pump. To avoid possible errors in flow measurement, this meter was recalibrated with an infrared 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 the ceiling corner away from the incense, and provided a good mixing without directly affecting the rising plume of smoke.

For each run three incense sticks were vertically inserted into holes on a pre-weighted plate. The height of the plate was then adjusted so that the tips of incense were located roughly at the half-height of the chamber. Incense sticks were briefly lighted with a propane lighter, and the flame was 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 of that for incense burning) was continuously drawn to purge the chamber for four additional hours after the combustion was completed. Each quartz filter (Gelman Series, 102 mm in diameter, about 500 mg in weight) was allowed to equilibrate in a dry box under 25 °C and 50% humidity for at least 24 h. Precision of filter weighing was evaluated by blank tests with plain filters. The average difference was to be 0.2 mg, which was only 0.1–1% (w/w) of the net weight of particulate collected in filter (50–150 mg).

2.3. Analysis

2.3.1. Semi-quantitative elemental and structural analyses

The pulverized and sieved (#100 mash, <0.149 mm) samples were used for X-ray fluorescence spectrometry (XRF) and X-ray diffraction spectroscopy (XRD) examinations. Semi-quantitative elemental analysis was carried out by a XEPOS XRF (model SPECTRO). Structures of samples were determined by a BRUKER XRD (model AXS/D8 ADVANCE) with Cu Kα radiation. Samples were scanned from 5° to 60° (2θ) with a scan rate of $4^{\circ}\,\mathrm{min}^{-1}$. The specific peak intensities 2θ values were recorded and identified by computer library system. By comparing the diffraction intensity of standards, structures of the raw materials of incense could be determined.

In this study, metallic elements content in raw material incense over $10\,\mu\mathrm{g\,g}^{-1}$ were selected for quantitative analysis. However, metals Ti, Sn, Y, Zr and Te, whose standard solutions are not available, were ignored. Thus, 11 metallic elements, including Na, Mg, K, Ca, Mn, Fe, Zn, Cu, Sr, Al and Ba, were chosen for the final quantitative analysis with ICP-AES.

2.3.2. Qualitative analysis

After weighing, the raw material incense and ash were placed in a Teflon vessel for 1 h. A 21 ml of 10% (v/v) ultra-pure nitric acid (Merck) and 7 ml of 10% (v/v) ultra-pure hydrochloric acid (Merck) were added to the container, which was placed in a Teflon bomb and loaded into the microwave oven for 30 min at a max power of 600 W (MLS ETHOS 900). Samples were subsequently analyzed by an inductively coupled plasma atomic emission spectrometer (ICP-AES, JY 38 Plus, Jobin-Yvon). Eleven major elements (Al, Ba, Ca, Cu, Fe, K, Mg, Mn, Na, Sr and Zn) were analyzed.

The method detection limit (MDL), defined as the minimum concentration of a substance that can be measured and reported with 99% confidence that the analyte concentration is greater than zero, was determined by analyzing a sample in a given matrix containing the analyte. The MDLs of Na, Mg, Al, K, Ca, Mn, Fe, Cu, Zn, Sr and Ba were found to be 29, 0.2, 27, 33, 5.1, 1.1, 3.2, 2.7, 3.6, 1.6 and 2.1 ppb, respectively.

3. Results and discussion

3.1. Metallic element in raw material of incense

3.1.1. Qualitative and semi-quantitative analysis

Table 2 shows the results of qualitative and semi-quantitative analysis of the nine incense (three samples for per incense, totally 27 samples) through XRF. Among the 33 metallic

Table 2
Semi-quantitative metallic content of the incense materials by XRF

Metals not found in all samples		Metals found in some samples		Metals found in all samples	
Element	Detection limit (μg g)	Element	Maximum concentration (μg g)	Element	Average concentration (μg g)
Mg[a]	5000	Al[a]	2900	Ca[a]	24,000
Zr	500	Ti	180	K[a]	7000
Te	63	Cu[a]	41	Ba[a]	1700
Ag	10	Y	11	Fe[a]	1500
Cr	6.3	Ni	3.8	Mn[a]	110
Sb	6.1	Cd	3.5	Sr[a]	77
Co	3.1	Pb	3.3	Sn	72
V	2.7			Zn[a]	8.9
U	1.9			Rb	5.9
Tl	1.5				
Th	1.4				
Hg	1.4				
Bi	1.3				
Ga	0.7				
Ge	0.7				
As	0.6				
Se	0.3				

$N = 3$ for each type of incense.
[a] These elements were quantitated by ICP-AES further.

elements that were qualitatively analyzed, 17 elements (Mg, Zr, Te, Ag, Cr, Sb, Co, V, U, Tl, Th, Hg, Bi, Ga, Ge, As and Se) in the nine incense failed to reach the detection limits. Sixteen metallic elements were detected from the 27 samples. Al, Ti, Cu, Y, Ni, Cd, Pb were detected from a few samples. Ca, K, Ba, Fe, Mn, Sr, Sn, Zn and Rb were detected from 27 samples, at average concentrations of 24,000, 7000, 1700, 1500, 110, 77, 72, 8.9 and 5.9 $\mu g\,g^{-1}$.

3.1.2. *Quantitative analysis*

Table 3 shows the result of qualitative analysis of 11 metallic elements among nine incense using an inductively coupled plasma atomic emission spectrometer (ICP-AES).

As the total metallic content (sum of the 11 metals quantified) incense A is the highest, the next is incense C, and the lowest one is incense F. The total metallic content varied among the nine types of incense, with a geometric mean and variation of 14 $mg\,g^{-1}$ and 105%, respectively. The most abundant metal was Ca, whose geometric mean content was 8.7 $mg\,g^{-1}$ among nine types of incense. The next was K (2.5 $mg\,g^{-1}$). The third-ranking group consisted of Al, Mg, Fe and Na (0.1–1.0 $mg\,g^{-1}$ each), while the fourth-ranking group consisted of Sr, Mn and Ba (0.01–0.1 $mg\,g^{-1}$ each), and traces of Cu and Zn. The sequence of the metallic contents in the raw material of incense were similar to Fang's [9] results (Fe > Zn > Pb > Cr > Mn > Cd > Ni > Cu). Furthermore, according to Roger [18], some significant microelements (Ca, K, Mg, Fe, Cu, Mn and Zn) were found in wood, whose pulverized form is used in incense production. Naturally, these elements were also detected in this study.

3.1.3. *Identifying critical components species*

Fig. 2 shows the results of XRD analyses of three incense A, C and H. Among the three samples with different quantities of total metal, the structures of most compounds containing Ca are an inorganic salt, synthetic $CaCO_3$. Quantities of other metals, such as Mg, Na, Fe, Al could not be measured since they were below the limit of detection of the analysis. Additionally, most of the compounds containing K were only proven to be complex organic compounds, while the ingredients of crystallized inorganic salt could not be measured since they were below the analysis minimum. According to market surveys and factory visits, the most commonly used inorganic salt is calcium carbonate, whose influence upon incense combustion is discussed in the following.

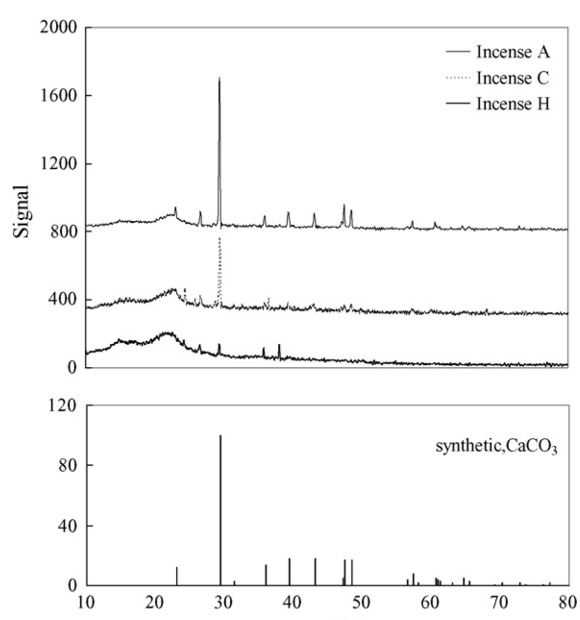

Fig. 2. XRD patterns for the crystal of three types incense (calcium carbonate).

Table 3
Quantitative metallic content of the incense materials by ICP ($mg\ g^{-1}$, $N=3$ per type)

Element	Incense A	B	C	D	E	F	G	H	I
Ca	60 ± 4	11 ± 0.5	19 ± 1	4.5 ± 0.5	5.8 ± 1	1.8 ± 0.2	10 ± 0.3	3.5 ± 0.1	13 ± 0.4
K	6.6 ± 0.3	3.4 ± 0.5	3.7 ± 0.5	1.1 ± 0.1	2.5 ± 0.6	1.8 ± 0.2	2.7 ± 0.06	1.3 ± 0.1	3.2 ± 0.5
Al	1.5 ± 0.1	0.60 ± 0.1	1.4 ± 0.5	0.18 ± 0.03	0.60 ± 0.2	0.24 ± 0.03	0.37 ± 0.03	0.24 ± 0.03	1.1 ± 0.1
Mg	1.5 ± 0.1	0.56 ± 0.03	0.64 ± 0.09	0.26 ± 0.05	0.37 ± 0.09	0.20 ± 0.03	0.41 ± 0.02	0.30 ± 0.03	0.61 ± 0.04
Fe	1.1 ± 0.04	0.43 ± 0.04	0.64 ± 0.1	0.17 ± 0.02	0.34 ± 0.07	0.26 ± 0.03	0.28 ± 0.01	0.25 ± 0.01	0.77 ± 0.07
Na	0.25 ± 0.04	0.77 ± 0.05	0.19 ± 0.01	0.26 ± 0.03	0.27 ± 0.01	0.27 ± 0.04	0.24 ± 0.05	0.27 ± 0.01	0.39 ± 0.01
Sr	0.45 ± 0.07	0.02 ± 0.00	0.36 ± 0.09	0.03 ± 0.01	0.03 ± 0.01	0.01 ± 0.00	0.09 ± 0.01	0.02 ± 0.00	0.05 ± 0.01
Mn	0.26 ± 0.04	0.08 ± 0.01	0.24 ± 0.05	0.04 ± 0.01	0.04 ± 0.01	0.04 ± 0.01	0.03 ± 0.01	0.04 ± 0.01	0.15 ± 0.03
Ba	0.05 ± 0.01	0.03 ± 0.01	2.6 ± 1	0.01 ± 0.00	0.44 ± 0.18	0.01 ± 0.00	0.02 ± 0.00	0.02 ± 0.00	0.22 ± 0.02
Cu	0.08 ± 0.02	0.001 ± 0.00	0.009 ± 0.00	N.D.	0.02 ± 0.03	0.001 ± 0.00	N.D.	0.000 ± 0.00	0.003 ± 0.00
Zn	0.02 ± 0.01	0.006 ± 0.00	0.02 ± 0.00	0.007 ± 0.00	0.004 ± 0.00	0.007 ± 0.01	0.004 ± 0.00	0.006 ± 0.00	0.08 ± 0.01
Total	72 ± 5	17 ± 1	29 ± 5	6.7 ± 0.7	11 ± 2	4.7 ± 0.4	15 ± 0.5	6.0 ± 0.2	20 ± 1

Average ± S.D.

3.2. Characteristics of burning incense

The physical characteristics of the burning of the nine types incense are shown in Table 4. The burning rate is the incense weight loss divided by combustion duration. The ash emission factor is calculated by the weight of ash accumulated on the plate divided by the incense weight loss. The particulate emission factor is calculated by dividing the weight gained on the filter by the incense weight loss. The ash and particulate generation rates are calculated, respectively, by dividing the weight of ash and particulate produced by the combustion duration. The differences of physical characteristics among different incense are discussed in the following.

3.2.1. Combustion duration and burning rate

The combustion durations of the nine incense was in the range 49–90 min. The variability of duration was approximately two times. The median value was 65 min, and the variation coefficient was 20%, showing that the combustion durations among different incense were obviously different. Considering incense weights, the burning rates were 15–35 $mg\ min^{-1}$, with variability of up to 2.4 times. The median value was 19 $mg\ min^{-1}$, and the variation coefficient was 33%. Thus, the burning rates of each of the nine incense were different. Additionally, the variation coefficients of the burning velocity among the same kinds of incense were within 5%. Since combustion duration is related to combustion type, combustion duration can also be easily used as the parameter for selecting incense.

3.2.2. Emission factor

The ash emission factor of the nine incense was in the range was 17–260 $mg\ g^{-1}$. The variability could be up to 15 times. The median value was 62 $mg\ g^{-1}$, and the variation coefficient was 94%. Thus, the ash emission factor among different types of incense was obviously different.

The particulate emission factor of the nine incense was in the range was 15–47 $mg\ g^{-1}$. The median value was 33 $mg\ g^{-1}$, and the variation coefficient was 30%. The maximum variability exceeded three times. Thus, the particulate emission factor among the nine incense was obviously different.

Roger [18] indicated that for most woods, the ash after complete combustion takes about 0.2–0.9% of the primary weight. Only the small part is larger than 1%. However, the ash after combustion took up about 1.7–26% of the primary weight (the burning part). Perhaps because inorganic salt with a high boiling point had been added during production, the unburned inorganic salt also fell into the ash after combustion. Additionally, burning

Table 4
Burning results of studied nine types incense ($N=3$ per type)

Incense	Combustion duration (min)	Burning rate ($mg\ min^{-1}$)	Emission factor ($mg\ g^{-1}$)		Generation rate ($mg\ min^{-1}$)	
			Particulate	Ash	Particulate	Ash
A	49 ± 1	35 ± 1	15 ± 1	260 ± 10	0.48 ± 0.04	8.1 ± 0.2
B	57 ± 1	18 ± 0.7	33 ± 2	70 ± 3	0.50 ± 0.03	1.1 ± 0.04
C	61 ± 2	23 ± 0.7	27 ± 2	123 ± 4	0.52 ± 0.03	2.4 ± 0.06
D	90 ± 2	15 ± 0.4	47 ± 1	26 ± 1	0.60 ± 0.02	0.33 ± 0.01
E	68 ± 2	17 ± 0.6	34 ± 2	48 ± 2	0.51 ± 0.05	0.71 ± 0.04
F	86 ± 4	15 ± 0.6	41 ± 2	17 ± 2	0.54 ± 0.04	0.21 ± 0.02
G	65 ± 2	19 ± 0.5	28 ± 2	62 ± 3	0.44 ± 0.03	0.98 ± 0.06
H	78 ± 2	15 ± 0.4	39 ± 4	30 ± 2	0.49 ± 0.05	0.38 ± 0.03
I	63 ± 1	19 ± 0.8	28 ± 3	78 ± 4	0.46 ± 0.05	1.2 ± 0.1

Average ± S.D.

incense led to incomplete combustion, since the ash contained some combustible organic substances.

Although the nine chosen incense were all hand-made, the variations of the combustion duration, burning rate, and of the particulate emission factor and ash emission factor among individual sticks from the same pack were within 10%.

3.2.3. Generation rate

The ash generation rate from burning nine incense was in the range 0.21–8.1 mg min^{-1}. The sequences of the ash generation rate and ash emission factor were identical, but the variability could be up to 40 times. The median value of the ash generation rate was 0.98 mg min^{-1} and the variation coefficient was 150%. Many differences were found between the ash generation rates of varied incense.

Notably, the particulate generation rate from burning nine incense was approximately 0.44–0.59 mg min^{-1}. The average particulate generation rate was 0.50 mg min^{-1}, and the variation coefficient was only 9%. Few differences were found between the particulate generation rates of varied incense. The values were a little lower than those of Lung and Hu [6]. Lung examined the incense smoke collected in the semi-open cylinder chamber and indicated that the particulate generation rates of two incense were 0.56 and 0.66 mg min^{-1}. The variation might be due to the smaller volume of chamber (approximately 14.5 cm^3) and lower flow rate (approximately 2.0 l min^{-1}). High concentrated smoke was accumulated in the small chamber and resulted in more serious incomplete combustion and thus a higher particulate emission factor. Furthermore, few particulates adhered to the inside surface of the chamber.

In conclusion, under the same burning conditions, including the air exchange rate, the volume of combustion chamber and the mass of incense, similar particulate generation rates were observed among different incense.

3.2.4. Correlation with combustion duration and particulate emission factor

Fig. 3 shows the combustion durations and the particulate emission of every stick of incense tested. The correlation of the combustion duration and the particulate emission with regression analysis ($r^2 = 0.93$, $p < 0.01$) was strongly positive. Thus,

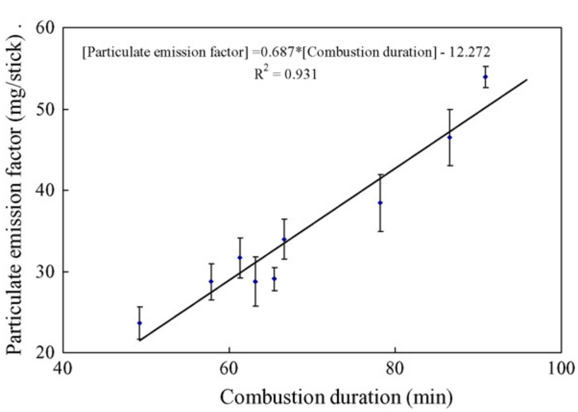

Fig. 3. Correlation between particle emission factor and combustion duration (each error value equals 1 S.D.).

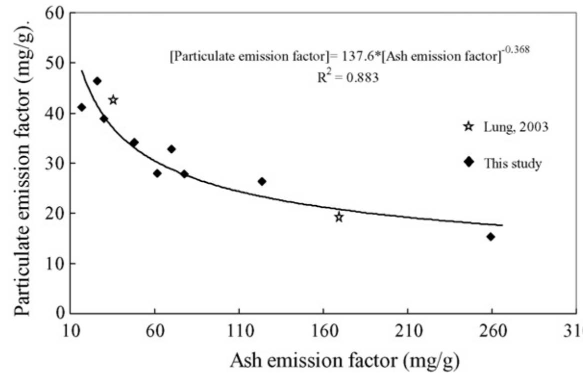

Fig. 4. Correlation between particulate and ash emission factors.

the longer the combustion duration will emitted more the particulate emissions in burning incense. Lung and Hu [6] found that the combustion durations of two types of incense were 57.1 and 72.0 min, while the particulate emission factors were 32.6 and 52.7 mg/stick, respectively. These data could also show the above-mentioned argument. The combustion duration can be measured more easily than the particulate emission, which has been proven to affect health. Consumers can choose the less health-damaging incense according to the above discussion.

3.2.5. Correlation between particulate and ash emission factors

Fig. 4 shows the correlation between the particulate and ash emission factors. Since incense combust incompletely, combustion generates suspended particulate and ash. The power formula for regression analysis was fitted. The analytical results show strongly negative correlations between the particulate and ash emission factors among the nine incense ($r^2 = 0.88$). The result is similar to that of Lung's study [6], in which several Taiwanese incense were examined. In Lung's study of two incense, the particulate emission factor of incense was, respectively, 19.8 and 43.6 mg g^{-1}, while the ash emission factors of incense was 172 and 37 mg g^{-1}, respectively. Therefore, the suspended particulate of incense combustion can be estimated from the ash emission factor, which is easier to measure than particulate emission factor. When burning incense of the same weight, the more the ash is produced, the less the particulate is emitted into the air. Consequently, incense that generates more ash pose less threat to the consumers' health.

3.3. Correlation between metallic content and characteristics of combustion

Since alkali metal ions, such as Na and K, are generally used as enhancers in smoldering [11], they could be applied to incomplete combustion (incense, for example) to cut down on the air pollution. The major metallic content (include Na, Mg, Al, K, Ca and Fe) and incense burning characteristics (include the burning rate, the particulate and ash emission factors) under the same conditions are discussed below. Table 5 shows the correlation coefficient r and value p between metallic content and characteristics of combustion. Each part is discussed as follows.

Table 5
Correlation between the major metals[a] content ($mg\,g^{-1}$ incense) and combustion characteristics

Element	Metallic content vs. burning rate		Metallic content vs. ash emission factor		Metallic content vs. particulate emission factor	
	r	*p*-Value	*r*	*p*-Value	*r*	*p*-Value
Ca	0.99	<0.001	0.99	<0.001	−0.84	<0.005
K	0.96	<0.001	0.96	<0.001	−0.94	<0.001
Al	0.83	<0.01	0.86	<0.005	−0.86	<0.005
Mg	0.98	<0.001	0.99	<0.001	−0.88	<0.005
Fe	0.88	<0.005	0.91	<0.001	−0.88	<0.005
Na	−0.15	>0.5	−0.10	>0.5	0.04	>0.5
Total metallic content[b]	0.99	<0.001	1.00	<0.001	−0.87	<0.005

[a] The major metals were individual metallic contents/total metallic content >1% (the average of nine incense types).
[b] Total metallic content was the sum of the 11 metals quantified.

This study found a positive correlation between the total metallic content and the ash emission factor. The correlation coefficient r was 0.99, $p < 0.001$, indicating that the total metallic content is one of the most important factors influencing the ash emission factor. Obvious positive correlations existed between Ca, Mg, K, Fe and Al ($r > 0.85$, $p < 0.005$) and the ash emission factor. No correlation was found between Na and the ash emission factor.

The analytical results show a strongly positive correlation ($r = 0.99$, $p < 0.001$) between the total metallic content and burning rate. Thus, the total metallic of the incense was one of the most important parameters that influence the burning rate. Similarly, strong positive correlations were observed between burning rates and contents of some metallic elements, including Ca, Mg, K, Fe and Al ($r > 0.83$, $p < 0.01$). However, no correlation was found between the burning rate and Na.

There is a negative correlation between the total metallic content and the particulate emission factor after combustion ($r = -0.87$, $p < 0.005$). Thus, the total metallic content was one of the most significant parameters influencing the particulate emission factor. Moreover, strong negative correlations were found between the particulate emission factor and elements K, Mg, Al and Ca ($r > 0.8$, $p < 0.005$). No relationship existed between the particulate emission factor and element Na.

There are a number of possible explanations for these results above. As Hawley and Wise [10] indicated, the ash combustion of woods generally contains 40–70% CaO, 10–30% K_2O, 5–10% MgO, 0.5–2.0% Fe_2O_3 and little Mn_3O_4, Al_2O_3 and Na_2O. This study conjectured that most Ca, Mg, Fe and Al exist in the form of inorganic salts either in the incense materials or in the ash. These high-melting inorganic salts may temporarily form a protective shield around the burning tip and insulate it from the cool surrounding air. The locally accumulated heat may therefore help subsequent combustion and effectively reduce the particulate emission. Finally, the metals dropped down in forms of inorganic salts as the ash during combustion. It is logical that a higher metallic content in the incense would lead to a higher ash emission factor.

The results are consistent with those reported by Kellogg et al. [12]. He indicated that high contents of K and Na (around 1500–2500 ppm) assist fabric combustion. Since the content of K in the incense materials was 1090–6550 ppm in this study, combustion would be likewise improved. The content of Na was merely 190–390 ppm, which was not found to affect the burning rate of incense in this study.

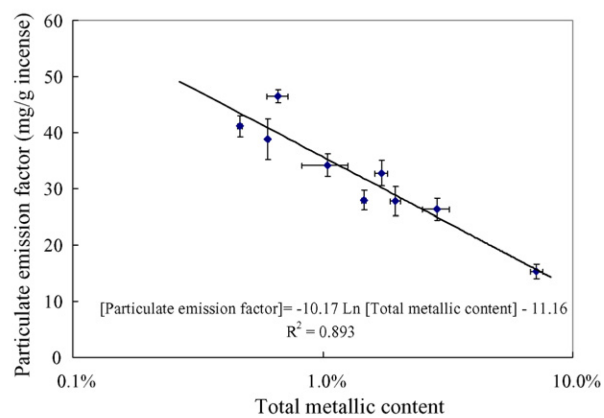

Fig. 5. Relationship between the total metallic content and the particulate emission factor (each error value equals 1 S.D., the total metallic content was sum of the 11 metals quantified).

As shown in Fig. 5, there was a negative correlation between the total metallic content and the particulate emission factors. Burning incense is an incomplete combustion, meaning that suspended particulates are created during incense burning. The exponential formula for regression analysis was fitted. According to the statistics mentioned above, appropriate amount of total metal added during producing the incense would reduce the level of suspended particulates in incense burning. When the total metallic content is increased from 0.5 to 2.0%, the particulate emission would be reduced by about 40%.

4. Conclusion

XRF was initially used to pre-screen and select 11 elements, which might be relevant to this study. More detailed quantitative analyses were then carried out by ICP-AES. The total metals content in different incense were obviously different. However, the order of quantities of metallic elements was similar in all incense. The contents of Ca and K were, respectively, the first and the second highest among all metallic elements found in the raw materials of the incense. The third highest contents were those of Al, Mg, Fe, Na and Ba, and the lowest were those of Sr, Mn, Cu and Zn. Most compounds containing Ca were inorganic salt, synthetic $CaCO_3$ which is added during production due to its low cost.

Under the same burning conditions, including the air exchange rate, the volume of combustion chamber and the incense mass, the combustion duration, burning rate, ash emission factor, particulate emission factor and ash generation rate strongly varied when burning different incense. However, the particulate generation rates were similar. Besides, burning an incense stick, the longer the combustion duration, the higher the total suspended particulate quantity, leading consumers to choose incense with short-term combustion. Additionally, with the same incense weight burned, the greater the emission of ash, the lower the emission of suspended particulate. Consumers can also use this information to choose less health-damaging incense.

Higher metallic contents in the incense materials result in higher burning rates. Additionally, when the total metallic content was below 2% of the raw materials, the total metallic content can be added to reduce the level of particulates during combustion.

Acknowledgement

The authors would like to thank the Taiwan National Science Council for financially supporting this research under Grant no. NSC 93-2211-E-006-039.

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