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Characteristics of emissions of air pollutants from burning of incense in a large environmental chamber

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Abstract

The objective of this study was to characterize the emissions of air pollutants from incense burning in a large environmental test chamber. Air pollutants emitted from ten types of commonly used incense manufactured in different regions were compared. The target pollutants included particulate matters (PM_{10}, $PM_{2.5}$), volatile organic compounds (VOCs), carbonyls, carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), methane (CH_4) and non-methane hydrocarbon (NMHC). The particulate matters emitted from all the incense significantly exceeded the *Recommended Indoor Air Quality Objectives for Office Buildings and Public Places in Hong Kong* (HKIAQO). The CO peak levels of seven incense types greatly exceeded the HKIAQO standard. The formaldehyde concentrations of six types of incense were higher than the HKIAQO. The highest formaldehyde level exceeded the standard by 2 times. The results indicated that the concentrations of benzene, toluene, methyl chloride and methylene chloride significantly increased with the burning of all incense tested. In addition, the benzene concentrations of all tested incense were significantly higher than the HKIAQO standard. Although Incense 2 and 6 were claimed to be environmental friendly, the quantity of the pollutants emitted was not observed to be lower than the others. It was observed that when comparing the gas pollutant emission factors between two major incense categories (i.e. traditional and aromatic), the traditional incense (i.e. Incense 1–6) had relatively higher values than aromatic incense (i.e. Incense 7–9). Generally, it was found that the VOCs emitted sequence was aromatic incense > tradition incense > church incense (i.e. Incense 10). However, the carbonyl compounds emission sequence was traditional incense > aromatic incense > church incense. The results show that incense burning is one of the important indoor air pollution sources for PM, CO and VOCs.

Keywords: Burning of incense; Environmental Chamber; Emission rate; Emission factor; VOCs

1. Introduction

Incense has been used for centuries for ceremonial purposes as well as to fragrance the environment. It is a traditional and common practice in many families in Hong Kong. With the rising environmental and health awareness, people are paying more attention to the problems caused by incense burning in the indoor and public environments.

A wide variety of substances used to produce incense include resins (such as frankincense and myrrh), spices, aromatic wood and bark, herbs, seeds, roots, flowers, essential oils and synthetic substitute chemicals which are used in the perfume industry (Jetter et al., 2002). Incense was discovered to be a significant source of polycyclic aromatic hydrocarbons (PAHs), carbon monoxide, benzene, isoprene and particulate matters (Koo et al., 1992; Li and Ro, 2000; Fan and Zhang, 2001). Roveri et al. (1998) found that some types of Chinese incense contained nitromusks that could cause allergic contact dermatitis and photosensitization. Per a study of particles and carbon monoxide (CO) associated

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with burning incense and cigarette, incense generated greater particulate mass, a larger count median particle diameter than burning of cigarette did (Nguyen et al., 1995). Tung et al. (1999) has identified that PM_{10} concentrations in homes with smoking or incense burning were 23% higher than those without such indoor air polluting activities.

Previous studies mainly focused on field investigations and tried to quantify a few air pollutants (e.g. CO, PM). The emission factors of air pollutants from incense burning were not well characterized. In addition, there is a lack of information on comparison of types and quantity of air pollutants emitted from different kinds of incense. Therefore, this study aimed to characterize and compare the emissions of air pollutants before, during and after incense burning in a large environmental chamber. In this study, the emission factors for $PM_{2.5}$, PM_{10}, CO_2, CO, NO_x, CH_4 and NMHC (in $mg\,g^{-1}$ incense burned), VOCs and carbonyl compounds concentrations were measured for ten different types of incense.

2. Materials and methods

2.1. Incense tested

Ten types of incense, which are commonly used in Hong Kong, were tested in this study. Selected incense types were manufactured in different countries (including China, Hong Kong, Singapore, Macau, India, Thailand, South Africa and Italy) and have various appearances (form, length, diameter and color) and scents. Most of the incense is in stick form which is manufactured with compounds attached to a wooden or bamboo stick. The general characteristics of these incenses are listed in Table 1.

Incense 1–6 were traditional incense used to worship deities. In a regular HK family, three incense sticks would be burned once per day on first or 15th day of Chinese lunar and one incense stick would be burned once per day on non-first or non-15th day of Chinese lunar. Three traditional incense sticks were burned simultaneously during each experiment. Among these, Incense 2 and 6 were claimed to be environmental-friendly incense, which was expected to cause less air pollution problems. While, Incense 7–9 were aromatic incenses which were claimed to have aromatherapy use. The common practice was burning one stick each time. On this ground, one stick each of Incense 7–9 was burned in each set of experiment. Incense 10 was church incense burned in a charcoal thurible.

2.2. Chamber experiments

The controlled experiments were conducted in a $18.26\,m^3$ stainless steel environmental test chamber maintained at a temperature of $23\pm0.5^\circ C$ and a relative humidity (RH) of $50\pm5\%$. A TSI portable Q-Trak (model 8550, TSI Inc.) was put in the chamber to ensure that the temperature and RH were within the required margin. The air exchange rate was maintained at $0.5\,h^{-1}$ to simulate the typical natural ventilation conditions. Fig. 1 shows the schematic diagram of the experimental set-up. The chamber was purged by blower air, which was passed through a clean air system with activated charcoal particle filters and High-Efficiency Particulate Air (HEPA) filters. Mixing fans were installed at the ceiling of the chamber to ensure adequate air mixing. Temperature control was achieved by placing the test chambers in incubator cabinets. The temperature of inlet air was controlled by using conditioning coils. RH is controlled by adding deionized water to the air system. Humidification was accomplished by bubbling a portion

Table 1
General information of incense

ID No.	Country of origin	Category	Form	Length of combustible part (cm)	Diameter of combustible part (mm)	Scent	Color	Avg. burn time (min)
Inc 1	China	Traditional	Stick	16.8	1.5	Not listed	Dark yellow	26
Inc 2	Hong Kong	Traditional	Stick	17.2	2.1	Not listed	Yellow	25
Inc 3	Singapore	Traditional	Stick	27.7	3.6	Not listed	Red	51
Inc 4	Hong Kong	Traditional	Stick	22.5	2.9	Sandalwood	Yellow	35
Inc 5	Macau	Traditional	Stick	24	2	Not listed	Pale yellow	37
Inc 6	Macau	Traditional	Stick	21.3	1.9	Sandalwood	Pale yellow	27
Inc 7	India	Aromatic	Stick	17.3	3.2	Sanskrit	Brown	39
Inc 8	Thailand	Aromatic	Stick	19.2	3.9	Lavender	Purple	31
Inc 9	South Africa	Aromatic	Bar	10.9	4.8	Rosemary	Rose	50
Inc 10	Italy	Church incense	Rock	n/a	n/a	Musk	Colorful	50

Note: n/a: The form of Incense 10 is rock. Thus, the length and diameter of combustible part is not applicable.

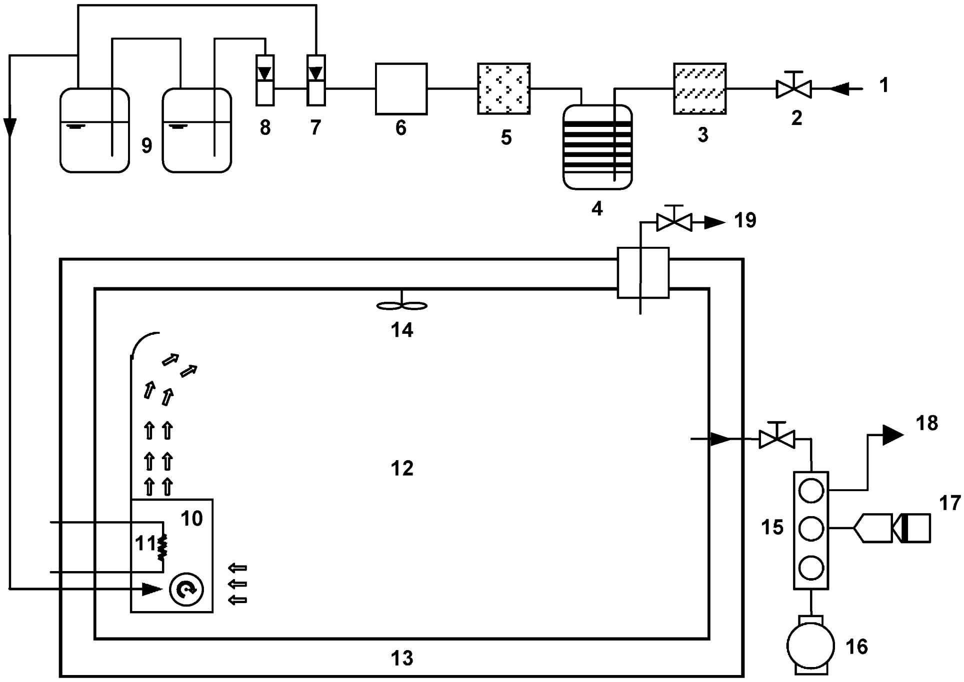

Fig. 1. Schematic diagram of the experimental set-up.

of the air stream through deionized water at a controlled temperature. Air samples were drawn from the chamber via nonabsorbent tubing into a pre-evacuating canister to determine VOCs. An aldehyde pump located outside the chamber was used to draw chamber air through sampling cartridges to determine the concentrations of carbonyl compounds. A Teflon tubing connected the chamber with a CO analyzer, a NO–NO_2–NO_x analyzer and a CH_4–NMHC analyzer.

Prior to the incense burning, the chamber was conditioned for about 4 h at standard test temperature, air exchange rate and RH. The background air samples were collected from the chamber to assess the background air quality. The background levels met the requirements of '*Large Chamber Test Protocol for Measuring Emissions of VOCs and Aldehydes*' (US EPA, 1999).

2.3. Sampling methods and analysis

$PM_{2.5}$, PM_{10}, CO_2, CO, NO_x, CH_4, NMHC, carbonyls and VOCs concentrations were measured for the ten incenses. Two Dust-Trak air monitors (model 8520, TSI Inc., MN, USA) were used to measure PM_{10} and $PM_{2.5}$ concentrations simultaneously in the chamber. A TSI portable Q-Trak (Model 8550, TSI Inc.) was used to monitor CO_2 concentrations. GFC Ambient CO Analyzer (Model 48, Thermo Environmental Instruments Inc.), Chemiluminescence NO–NO_2–NO_x Analyzer (Model 42C, Thermo Environmental Instruments Inc.) and Direct Methane, Non-Methane Hydrocarbon Analyzer (Model 55C, Thermal Environmental Instruments Inc.) were used to quantify CO, NO_x, CH_4 and NMHC concentrations, respectively. A five-point calibration and a zero check were performed daily for each instrument with standard gas at known concentrations.

For VOCs, grab samples were obtained before and after burning (0.5 h after the incense has extinguished). The samples during burning were time-integrated samples, drawn at a flow rate of 38.08–79.57 ml min^{-1} (depending on the burning time of the incense) using mass flow controllers (model FC4101CV-G, Autoflow Inc., CA). After sampling, the samples were analyzed within 3 h. Prior to sampling, sequential evacuating and pressurizing with humidified zero air was used to clean the canisters. 10% blank sample canisters filled with standard gas containing target organic compounds of known concentrations were conducted during sample collection and storage with other sampling canisters for GC/MS analysis. Prior to the experiments, background air samples were collected to ensure the background levels do not exceed 10 $\mu g\,m^{-3}$ of TVOC and 2 $\mu g\,m^{-3}$ of many individual VOC. Detailed description of the analysis can be found in Lee et al. (2002). A total of 38 VOCs species were identified by the GC/MSD system and 11 species were selected in this study.

Carbonyls were collected by drawing the chamber air through a silica gel cartridge impregnated with acidified 2,4-dinitrophenylhydrazine (Waters Sep-Pak DNPH-silica). An ozone scrubber was connected before the

Table 2
Detection ranges and limits of the sampling methods

Air parameter	Detectable mechanism	Range	Minimum detection limit
Carbon dioxide (CO2)	Non-dispersive infra-red (NDIR)	0–5000 ppm	1 ppm
Carbon monoxide (CO)	Non-dispersive infra-red (NDIR)	0–50 ppm	0.1 ppm
Nitrogen oxides (NO_x)	Chemiluminescence based analyzer	0–1000 ppb	0.40 ppb
Methane (CH4) and non-methane hydrocarbon (NMHC)	Flame ionization detection	0–200 ppm (non-methane hydrocarbon)	0.02 ppm methane 0.05 ppm NMHC as propane
VOCs	Gas chromatography mass specific detector (GCMSD) TO-14 method	0–5000 μg/m^3	0.20 ppb
Carbonyls	High performance liquid chromatography (HPLC) TO-11 method	0–5000 μg/m^3	0.20 ppb

DNPH-silica cartridge in order to prevent interference from ozone. A flow rate of approximately 900 ml/min was used and the sampling period before incense burning was 1 h and after incense burning was 0.5 h. The sampling period during burning depended on the burning time of each incense. Flow rate measurements were made at the start and end of each sample collection period using a soap-bubble flow meter (Gilian Gilibrator 2, Enviro-Equipment, Inc., N.C.). The cartridges were then measured using reverse-phase high-performance liquid chromatography (HPLC) to determine the concentrations of the carbonyl compound. Three blank cartridges were analyzed from each batch of 50 cartridges to assess the cartridge background. Background air samples were collected to ensure background formaldehyde levels do not exceed 2 μg m^{-3}. A total of 8 carbonyl compounds were identified in this study, with a detection limit of 0.2 ppbv. All analysis procedures were performed according to the US EPA method TO-11 (USEPA, 1998a, b).

The incense tested was weighed using a micro-balance with an accuracy of 0.01 mg. The ranges and limits of the detection of analytical methods are summarized in Table 2. Duplicated samples were collected for all incense types in order to ensure the consistency and accuracy of sampling data (Table 3).

Table 3
Recommended indoor air quality objectives for office buildings and public places in HK

Parameter	Unit	8-h average	
		Level 1[a]	Level 2[b]
Carbon dioxide (CO_2)	ppm	<800	<1000
Carbon monoxide (CO)	ppm	<1.750	<8.750
Nitrogen dioxide (NO_2)	ppm	<0.021	<0.08
Respirable suspended particulates (RSP)	mg m^{-3}	<0.02	<0.18
Formaldehyde (HCHO)	μg m^{-3}	<30	<100
		Levels 1 and 2	
Benzene	μg m^{-3}	<16.1	
Toluene	μg m^{-3}	<1092	
Ethylbenzene	μg m^{-3}	<1447	
Xylene	μg m^{-3}	<1447	
Chloroform	μg m^{-3}	<163	

[a] Level 1—represents very good indoor air quality that a high-class and comfortable building should have.

[b] Level 2—represents indoor air quality that provides protection to the public at large including the very young and the aged.

2.4. Modelling of emissions

The emission rates and emission factors for the ten incense types were determined by using a single-compartment mass balance model (Fan and Zhang, 2001). The concentration of the pollutant in the chamber could be described with the following equations:

$$C = P(1 - e^{-kt})/Vk \text{ (when } 0 \leqslant t \leqslant T), \quad (1)$$

$$C = C_{\max}(e^{-k(t-T)}) \text{ (when } t > T), \quad (2)$$

where C is the pollutant concentration (mg m^{-3}) in the chamber, P is the emission rate (mg h^{-1}), V is the volume of the chamber (m^3), $C_{\max}$ is the maximum pollutant concentration (mg m^{-3}) in the chamber, i.e., the concentration at the time when the incense was extinguished, k is the pollutant removal rate (h^{-1}), t is time (h): $t = 0$ when the incense was ignited; $t = T$ when the incense was extinguished. The value of k is the regression slope of the plot of ln(C) versus t, derived from Eq. (2). The value of P/Vk is the regression slope of the plot of C versus $(1 - e^{-kt})$. Then, P can be obtained because V is known. Background concentrations of all the measured pollutants were subtracted in determination of k and P/Vk using the above equations. The burning rate B ($g\,h^{-1}$) was obtained from the amount (g) of incense burnt and the duration (h) of burning, the emission factor E_f ($mg\,g^{-1}$) was calculated using the following equation:

$$E_f = P/B. \tag{3}$$

3. Results and discussion

3.1. Emission rates and emission factors

Emission rates (in milligrams per hour) and emission factors (in milligrams per gram of incense) for $PM_{2.5}$, PM_{10}, CO_2, CO, NO, NO_2, NO_x, CH_4 and NMHC emitted from the burning of ten types of incense are summarized in Table 4. The squared correlation coefficient (R^2), a measure of the degree to which the mass balance model fitted the real-time measured target air pollutants concentrations, ranged from 0.8188 to 0.9994.

It can be seen that Incense 10, the church incense, had the highest emission factors for CO_2 and CO (i.e. 1070.9 and 227.7 $mg\,g^{-1}$ incense, respectively). The main reason was that the church incense was burnt with the charcoal thurible, which would emit significant amount of CO and CO_2. Incense 9, the incense bar from South Africa had the lowest emission factors for CO and NMHC. Incense 8 had the lowest NO and NO_x emission factors. In general, it was discovered that the traditional incense types (i.e. Incense 1–6) had relatively higher emission factors than the aromatic incense types (i.e. Incense 7–9).

The emission factors (in $mg\,g^{-1}$ incense) for CO_2, CO, NO, NO_2, NO_x, CH_4, NMHC, $PM_{2.5}$, and PM_{10} ranged between 1.4–1070.9, 1.0–227.7, 0.3–2.6, 0.1–0.7, 0.4–3.3, 0.4–9.6, 0.1–19.1, 7.7–205.4, and 8.5–241.2, respectively. The NO_x emission factor of Incense 6 was almost eight times of that of Incense 8 and the CH_4 emission factor of Incense 5 was 24 times of that of Incense 10. The results implied that the amount of air pollutants emitted from different types of incense varied considerably.

Ranges of target air pollutants concentrations measured in the environmental test chamber are listed in Table 5. The lower values are the background concentrations at the beginning of the experiments. It is noted that CH_4 and NMHC concentrations do not increase significantly due to incense combustion except Incense 3. Most of the peak concentrations of all pollutants were observed during or immediately after extinguishing the incense, which well fitted the mass balance model used. The 8-h average PM_{10}, CO_2, CO and NO_2 levels (i.e., 0.18 $mg\,m^{-3}$, 1000 ppm, 8.75 ppm and 79 ppb, respectively) are specified by *Recommended Indoor Air Quality*

Table 4
Emission rates (a) and emission factors (b) of incense

	Inc 1	Inc 2	Inc 3	Inc 4	Inc 5	Inc 6	Inc 7	Inc 8	Inc 9	Inc 10
(a)Emission rate ($mg\,h^{-1}$)										
$PM_{2.5}$	227.6	205.2	300.9	242.6	372.6	28.4	9.8	85.4	23.4	2160.3
PM_{10}	243.3	210.1	341.8	275.1	389.4	31.9	10.8	92.5	28.1	2536.6
CO_2	99.7	4.7	4305.0	1092.1	819.4	2251.7	52.5	516.1	176.0	7994.8
CO	401.3	608.1	794.7	461.3	617.2	642.9	140.2	150.7	1.9	653.0
NO	2.2	4.3	7.7	3.8	1.5	7.8	1.9	0.5	1.0	3.7
NO_2	0.3	0.3	1.1	0.6	0.2	1.6	0.9	0.1	0.1	0.5
No_x	2.9	4.6	8.8	4.4	1.9	9.8	2.6	0.6	1.0	4.3
CH_4	16.7	23.8	51.5	8.3	34.4	28.3	1.8	4.7	12.1	1.2
NMHC[a]	29.0	28.1	56.0	21.9	48.4	24.0	24.3	12.3	0.1	24.1
(b)Emission factor ($mg\,g^{-1}$ incense)										
$PM_{2.5}$	99.7	62.4	41.5	71.8	104.0	9.6	7.7	11.8	12.6	205.4
PM_{10}	106.5	63.8	47.1	81.4	108.7	10.8	8.5	12.8	15.1	241.2
CO_2	43.7	1.4	593.7	323.3	228.7	759.8	41.1	364.4	94.6	1070.9
CO	175.7	184.9	109.6	136.6	172.2	217.0	110.0	106.4	1.0	227.7
NO	1.0	1.3	1.1	1.1	0.43	2.6	1.5	0.3	0.6	1.3
NO_2	0.1	0.1	0.14	0.2	0.1	0.5	0.7	0.1	0.1	0.2
No_x	1.3	1.4	1.2	1.3	0.5	3.3	2.1	0.4	0.5	1.5
CH_4	7.3	7.2	7.1	2.5	9.6	9.6	1.5	3.3	6.5	0.4
NMHC[a]	12.7	8.5	7.7	6.5	13.5	8.1	19.1	8.7	0.1	8.9

Note: All values were averaged for duplicated experiments.

[a] NMHC was converted by C_3H_8.

Table 5
Ranges of pollutants concentrations during incense burning

Incense ID	CO_2 (ppm)	CO (ppm)	NO (ppb)	NO_2 (ppb)	NO_x (ppb)	CH_4 (ppm)	NMHC (ppm)	$PM_{2.5}$ ($mg\,m^{-3}$)	PM_{10} ($mg\,m^{-3}$)
Inc 1	566–572	0.96–10.42	5.8–77.5	4.1–20.4	9.9–92.0	1.16–1.96	0.04–0.44	0.015–6.16	0.018–6.872
Inc 2	562–573	0.96–17.34	5.1–120.1	5.1–42.2	10.2–140.9	1.19–2.59	0.04–0.64	0.032–5.092	0.058–5.586
Inc 3	562–730	0.87–38.77	6.4–379.8	4.6–48.2	10.0–427.2	1.17–4.57	0.04–1.64	0.012–18.264	0.016–20.877
Inc 4	557–598	0.87–16.47	6.2–133.9	4.8–39.8	11.0–148.8	1.11–1.51	0.04–0.64	0.008–8.370	0.01–9.55
Inc 5	554–594	1.01–20.83	6.1–73.6	4.3–23.3	10.4–88.8	1.19–2.99	0.04–1.24	0.018–13.805	0.20–15.241
Inc 6	550–588	0.86–16.57	6.3–187.5	4.3–37.9	10.6–223.5	1.19–2.49	0.04–0.64	0.041–1.034	0.053–1.219
Inc 7	568–809	0.96–7.65	6.2–94.0	4.1–25.2	10.3–116.4	1.16–1.56	0.04–0.64	0.032–0.721	0.045–0.788
Inc 8	566–867	0.97–5.37	6.4–22.3	4.2–8.9	10.6–30.4	1.16–1.36	0.04–0.44	0.023–2.411	0.027–2.827
Inc 9	570–850	0.98–1.08	5.6–58.9	4.8–15.3	10.4–74.2	1.17–2.37	0.04–0.64	0.028–2.178	0.035–2.67
Inc 10	568–938	0.98–37.78	6.2–171.5	5.2–20.1	11.4–191.4	1.17–2.37	0.04–0.64	0.018–38.351	0.024–46.285

Objectives for Office Buildings and Public Places in Hong Kong (HKIAQO, HKEPD, 1999). The CO_2 and NO_2 peak concentrations from all the tested incense types satisfy the criteria (1000 ppm, 79 ppb) set by HKIAQO. However, the CO peak levels of seven incense types significantly exceeded the HKIAQO standard. Especially for Incense 3 and 10, the CO peak level exceeded 3 times more than the HKIAQO criteria, and exceeded the US EPA's National Ambient Air Quality Standards (NAAQS, US EPA, 2000) for 1-h CO of 35 ppm. Although Incense 2 and 6 were claimed to be environmental-friendly, the quantity of the pollutants emitted was not observed to be lower than the others. Both the CO concentrations of incense 2 and 6 exceeded the HKIAQO. Nevertheless, the NO and NO_x emission factors of incense 6 were the highest among all. It is notable that the particulate matters from all the incense significantly exceeded the requirement.

3.2. Carbonyl compounds

Fig. 2 presents the concentrations of eight carbonyl compounds measured for the ten types of incense during and after incense combustion. The burning concentration levels of formaldehyde, butyraldehyde and valeraldehyde were observed to be higher than after-burning levels. However, the levels of acetaldehyde, acetone, propionaldehyde and methacrolein reach the peaks after the incense was extinguished. The 8-h average formaldehyde concentration recommended by HKIAQO is $100\,\mu g\,m^{-3}$. The result shows that the formaldehyde concentrations of six types of incense were higher than the HKIAQO. Nevertheless, the formaldehyde concentrations of Incense 3 both during and after burning were substantially higher than the standard value; the burning level exceeded the standard by 2 times. Ho and Yu (2002) found that the formaldehyde levels in both the temple yard and the home surpassed the WHO guideline. This implies that the indoor incense-burning environment adversely affects human health.

The carbonyl compounds concentrations emitted by the incense were normalized by the incense mass. The normalized carbonyl compounds concentrations are shown in Fig. 3. The figures of two incense categories (i.e. traditional and aromatic) do not differ significantly for formaldehyde, acetaldehyde, acetone and methacrolein. However, aromatic incense types generally have lower acrolein, butyraldehyde and propionaldehyde concentrations than traditional ones.

3.3. VOCs

Table 6 shows the temporal changes of VOCs concentrations during and after burning of ten types of incense and the concentrations normalized by the incense mass. It was found that benzene, toluene, methyl chloride and methylene chloride concentrations increased significantly during burning of the ten incense types. In addition, the average concentrations of other individual VOCs, such as ethylbenzene, *m,p*-xylene, styrene and *o*-xylene were also observed to increase with incense combustion. From Table 6b, it was found that the temporal variations of some VOCs concentrations showed different patterns for traditional and aromatic incense. For example, the majority of methylene chloride concentrations increased after incense burning for traditional incense. However, methylene chloride concentrations from all three aromatic incense decreased after burning of incense. In general, aromatic incense and the church incense would emit more VOCs species than traditional incense. The concentrations for some VOCs were even higher after burning than during burning, which implies that human exposure periods may be long. It was inspected that when some incense was ignited, it would emit black smoke. The black smoke may include a large amount of some VOCs so that the concentrations after burning were higher than during burning.

The benzene and toluene levels recommended by the HKIAQO are 16.1 and $1092\,\mu g\,m^{-3}$, respectively. From

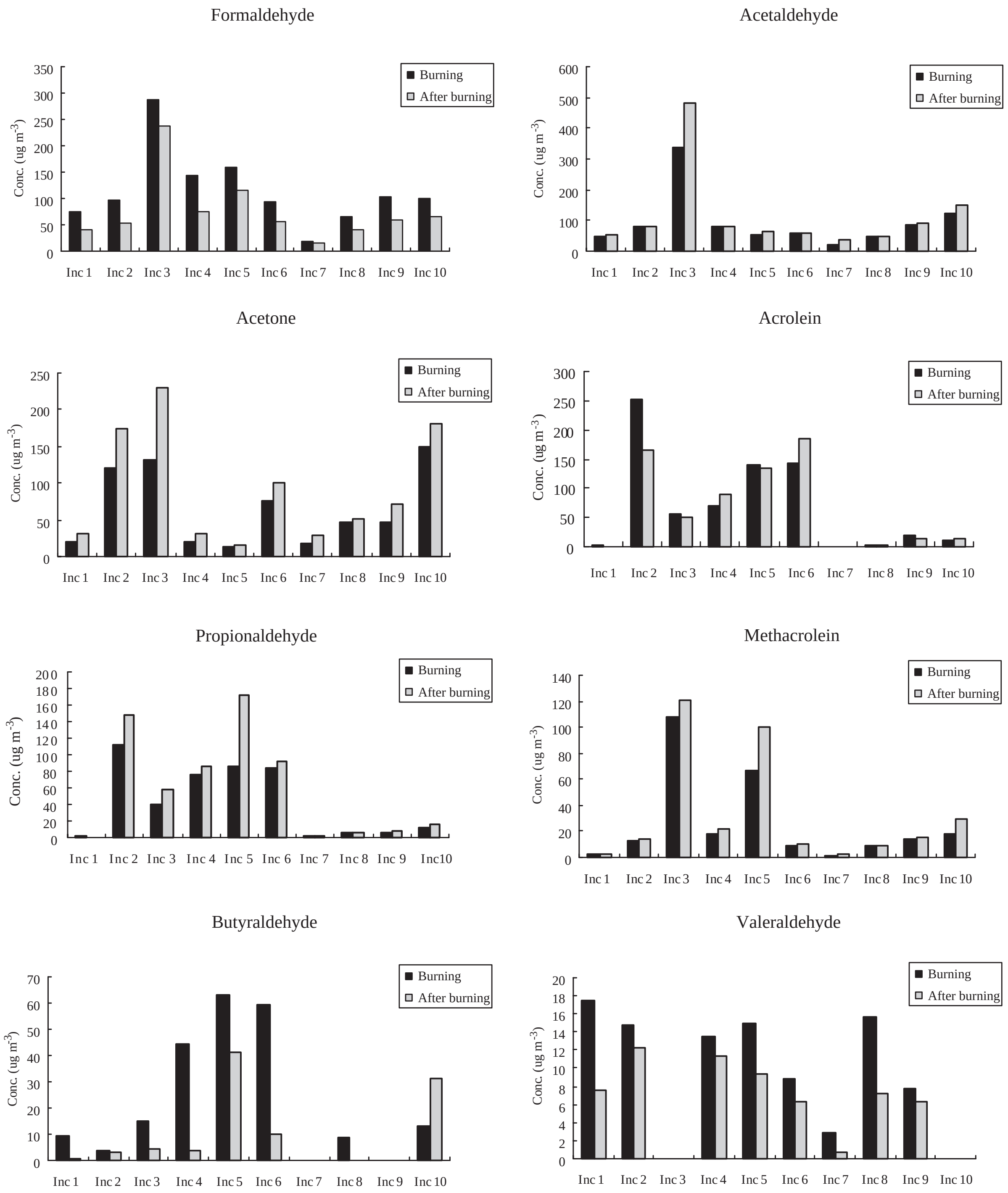

Fig. 2. Carbonyl compounds concentrations of incense burning.

Table 6a, it can be seen that the benzene concentrations of all tested incense are significantly higher than the standard. Meanwhile, all of the toluene levels do not exceed the standard. Löfroth et al. (1991) found that emissions could increase the indoor benzene concentrations above urban air background levels of 2–20 μg m^{-3}, which coincides with the findings of this study.

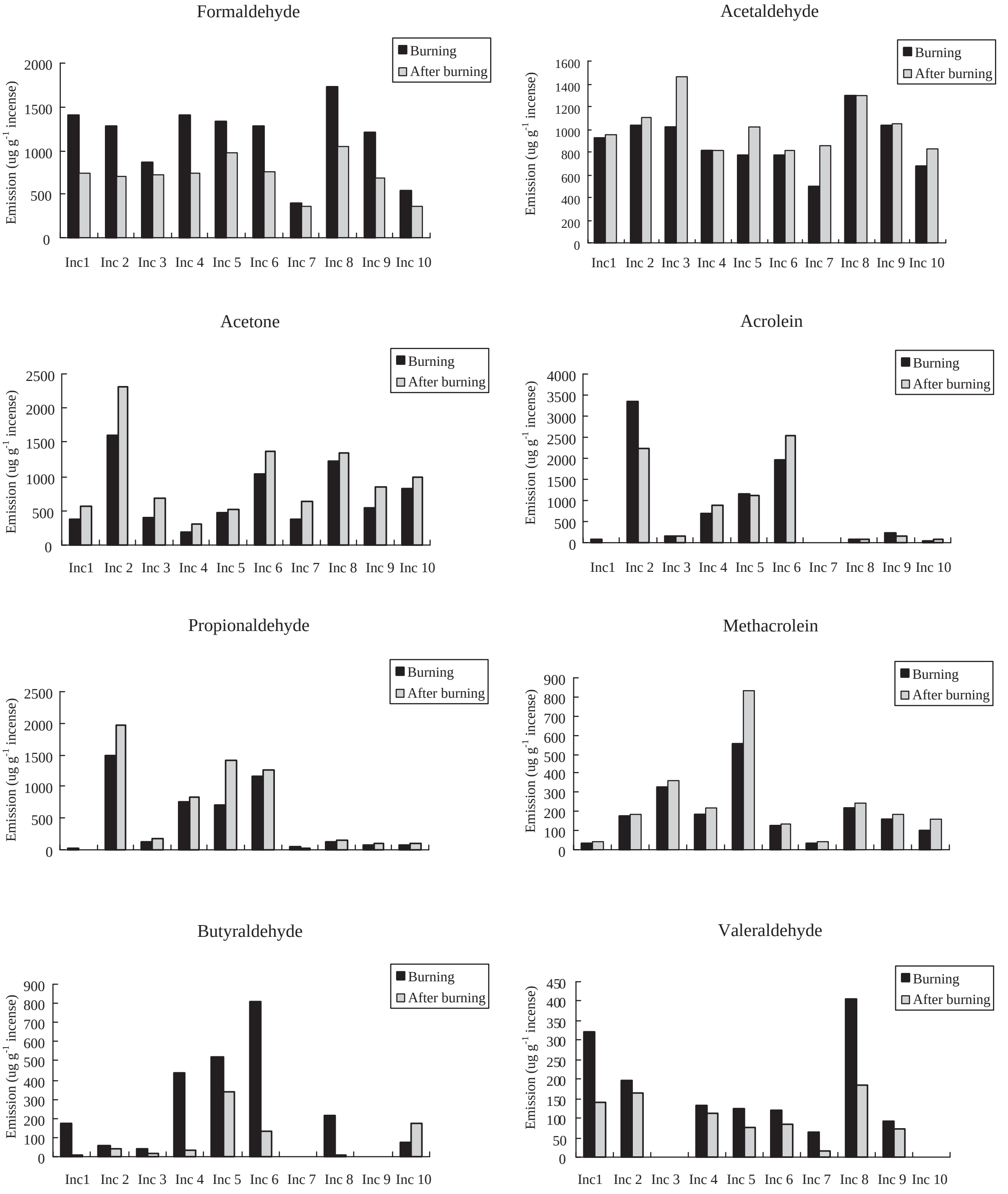

Fig. 3. Normalized carbonyl compounds emission of incense burning.

3.4. Comparisons of different types of incense

The comparisons of different types of incense were shown in Table 7. For gas pollutants, emission factors were compared. In general, the traditional incense would emit more gas pollutants than the aromatic incense except for NO_2. However, the church incense had the highest emission factors for CO_2 and CO due to the

Table 6
Temporal changes of (a) VOCs concentrations and (b) normalized VOCs concentrations for ten types of incense

	Inc 1		Inc 2		Inc 3		Inc 4		Inc 5		Inc 6		Inc 7		Inc 8		Inc 9		Inc 10	
	i	ii	i	ii	i	ii	i	ii	i	ii	i	ii	i	ii	i	ii	i	ii	i	ii
(a) VOCs ($\mu g\,m^{-3}$)																				
Methyl chloride	4.4	8.0	33.2	59.4	22.7	38.7	16.8	29.6	52.5	91.1	n.d.	n.d.	6.3	7.1	11.6	17.7	12.1	18.2	n.d.	n.d.
Methylene chloride	2.7	3.1	37.0	74.8	34.6	45.6	28.9	28.7	53.1	64.7	14.6	20.1	2.3	1.5	2.7	1.8	33.7	29.4	103.0	162.0
cis-1,2-dichloroethene	1.1	3.4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	7.9	9.5	n.d.	n.d.	1.4	3.4	15.8	27.5	0.8	3.6
Chloroform	n.d.	n.d.	n.d.	n.d.	7.5	9.4	n.d.	n.d.	42.1	61.6	7.1	9.5	n.d.	n.d.	1.4	1.7	3.6	9.2	3.1	6.3
1,2-dichloroethane	1.61	2.97	n.d.	n.d.	15.4	21.1	n.d.	n.d.	16.1	21.8	5.8	n.d.	6.0	9.9	1.0	1.7	5.2	11.9	14.5	32.7
Benzene	22.8	46.7	20.2	41.5	86.4	117.0	17.8	41.2	22.7	39.4	65.4	79.6	96.0	112	41.4	69.6	35.1	58.2	34.1	64.2
Toluene	29.4	17.1	10.3	11.1	87.7	98.5	11.0	17.5	4.8	43.2	48.3	51.6	17.0	20.1	9.8	13.8	31.3	48.8	44.6	80.4
Ethylbenzene	111.0	0.9	n.d.	n.d.	54.8	0.8	35.7	2.2	5.1	0.9	4.1	3.7	0.6	0.9	0.9	0.4	1.3	2.38	10.4	21.2
m,p-xylene	0.7	0.7	n.d.	n.d.	3.0	1.1	3.8	2.0	1.4	0.5	2.3	2.6	0.7	0.9	0.6	0.5	1.1	1.9	10.5	20.9
Styrene	1.7	2.9	n.d.	n.d.	6.3	8.2	1.3	3.0	1.7	8.2	5.2	6.2	2.9	4.1	n.d.	n.d.	2.3	5.0	7.1	13.2
o-xylene	95.6	0.4	n.d.	n.d.	44.0	0.4	n.d.	n.d.	n.d.	n.d.	1.1	0.9	3.3	1.2	0.7	0.2	n.d.	n.d.	2.4	4.6
(b)VOCs ($\mu g\,g^{-1}$ incense)																				
Methyl chloride	81	147	442	792	69	117	165	291	434	754	n.d.	n.d.	82	92	299	458	143	215	n.d.	n.d.
methylene chloride	50	58	493	996	105	138	284	282	440	535	201	276	30	20	70	47	398	347	567	893
cis-1,2-dichloroethene	20	63	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	108	131	n.d.	n.d.	37	86	186	324	4	20
Chloroform	n.d.	n.d.	n.d.	n.d.	23	28	n.d.	n.d.	349	510	97	129	n.d.	n.d.	37	43	42	108	17	35
1,2-dichloroethane	30	55	n.d.	n.d.	47	64	n.d.	n.d.	133	180	79	n.d.	78	130	26	43	62	140	80	180
Benzene	420	862	269	553	261	353	175	405	188	326	895	1090	1252	1455	1067	1796	413	686	188	354
Toluene	542	315	138	148	265	298	108	172	39	358	661	707	221	262	254	355	369	575	246	443
Ethylbenzene	2048	16	n.d.	n.d.	165	2	351	22	42	7	57	50	8	12	24	11	16	28	57	117
m,p-xylene	13	13	n.d.	n.d.	9	3	38	20	11	4	31	36	9	12	16	13	12	22	58	115
Styrene	31	53	n.d.	n.d.	19	25	13	30	14	68	71	85	37	54	n.d.	n.d.	27	59	39	73
o-xylene	1764	7	n.d.	n.d.	133	1	n.d.	n.d.	n.d.	n.d.	15	12	43	16	18	6	n.d.	n.d.	13	25

Note: (i) Time between ignition and completion of incense burning and (ii) after incense burning (30 min after completion of the incense burning).
n.d.: Not detected.

thurible burnt with the incense. Löfroth et al. (1991) found the incense produced approximately 180–220 mg of CO per gram of incense burned, which is similar to our values. For VOCs, the aromatic incense had the highest concentrations for benzene, *cis*-1,2-dichloroethene and 1,2-dichloroethane. The church incense had the highest methylene chloride and *m,p*-xylene concentrations. Generally, it was found that the VOCs emitted sequence was aromatic incense > tradition incense > church incense. Löfroth et al. (1991) found that 420–440 μg of benzene was produced per gram of incense burned, which is close to the benzene emissions of the traditional and church incense. However, the aromatic incense was found to produce significantly higher benzene emissions than the values in the Löfroth et al. (1991) study. The general carbonyl compounds emission sequence was traditional incense > aromatic incense > church incense. Among three incense types, the tradition one had the highest emissions for formaldehyde, acrolein, propionaldehyde, methacrolein and butyraldehyde. The comparisons implied that the amount of air pollutants emitted from different types of incense varied considerably.

4. Conclusion

Ten types of incense were tested in order to determine and investigate the characteristics of air pollutant emissions associated with indoor incense burning. It was observed that the levels of CO_2, CO, NO_x, CH_4, NMHC, $PM_{2.5}$, PM_{10}, carbonyl compounds and VOCs increased due to the burning of incense. The CO peak levels of seven incense types greatly exceeded the HKIAQO standard. The formaldehyde concentrations of six types of incense were higher than the HKIAQO. In addition, the benzene concentrations of all tested incense were significantly higher than the HKIAQO standard. This implies that indoor incense combustion has adverse effects on human health. It is also concluded that there is variability among the ten types of incense (with regards to carbonyl compounds, VOCs, PM and gas pollutants). Generally, the traditional incense type had the highest gas emission factors among three incense types. It was also found that the VOCs emitted sequence was aromatic incense > tradition incense > church incense. However, the carbonyl compounds emission sequence was traditional incense > aromatic incense > church

Table 7
Comparisons of three incense types

Emission factor (mg g^{-1} incense)	Traditional incense[a]	Aromatic incense[b]	Church incense
CO_2	325.1	166.7	1070.9
CO	166	72.5	227.7
NO	1.3	0.8	1.3
NO_2	0.2	0.3	0.2
NO_x	1.5	1	1.5
CH_4	7.2	3.8	0.4
NMHC	9.5	9.3	8.9

VOCs (μg g^{-1} incense)	Burning	After burning	Burning	After burning	Burning	After burning
Methyl chloride	198.4	350.1	174.7	254.9	n.d.	n.d.
Methylene chloride	261.8	380.7	165.7	138.0	566.9	892.7
Cis-1,2-dichloroethene	21.3	32.2	74.4	136.8	4.2	19.6
Chloroform	78.0	111.3	26.3	50.4	17.3	34.6
1,2-dichloroethane	48.0	59.7	55.0	103.9	79.7	180.2
Benzene	367.9	732.5	910.7	1312.1	188.1	354.1
Toluene	292.2	332.9	281.3	397.5	245.8	443.4
Ethylbenzene	443.9	16.2	15.8	16.9	57.4	116.7
m,p-xylene	17.0	12.6	12.5	15.4	57.7	115.3
Styrene	24.7	43.3	21.4	37.5	38.9	72.8
o-xylene	318.7	3.3	20.4	7.2	13.2	25.3

Carbonyls (μg g^{-1} incense)	Burning	After burning	Burning	After burning	Burning	After burning
Formaldehyde	1261.3	767.7	1109.0	696.7	549.4	359.9
Acetaldehyde	891.4	1028.6	940.5	1067.3	679.2	823.7
Acetone	676.4	961.4	717.0	942.9	822.7	999.1
Acrolein	1230.8	1154.6	106.1	72.3	54.7	81.7
Propionaldehyde	709.6	945.2	89.6	90.6	68.8	93.2
Methacrolein	232.6	295.7	138.9	159.5	97.4	162.4
Butyraldehyde	341.0	95.5	72.6	1.7	72.8	171.5
Valeraldehyde	149.4	96.1	187.0	92.0	n.d.	n.d.

[a] The values were averaged by 6 traditional incense.
[b] The values were averaged by 3 aromatic incense.

incense. The emission factors (mg g^{-1} incense) were: CO_2, 1.4–1070.9; CO, 1.0–227.7; NO, 0.3–2.6; NO_2, 0.1–0.7; NO_x, 0.4–3.3; CH_4, 0.4–9.6; NMHC, 0.1–19.1; $PM_{2.5}$, 3.3–87.8 and PM_{10}, 4.3–123.6, respectively. The emission rates and emission factors obtained in this study can be used in risk assessment for indoor incense burning. Further experiments on emissions of heavy metals and EC/OC are considered necessary in the upcoming study.

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