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Physical characteristics of nanoparticles emitted from incense smoke

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Abstract

Incense is habitually burned in various religious settings ranging from the Eastern temples to the Western churches and in residential homes of their devotees, representing one of the most significant sources of combustion-derived particulate matter in indoor air. Incense smoke has been known to be associated with adverse health effects, which could be due to the release of the submicron-sized particles, including ultrafine and nanoparticles. However, there is currently a lack of information available in the literature on the emission rates of particles from incense smoke in terms of their particle number, a metric generally regarded as a better indicator of health risks rather than the particle mass. In this study, real-time characterization of the size distribution and number concentration of sub-micrometer-sized particles (5.6–560 nm) emitted from incense smoke was made, for the first time, for four different brands of sandalwood and aloeswood incense sticks commonly used by different religious groups. In addition, the respective emission rates were determined on hourly and mass basis based on mass balance equations. The measurements showed that the particle emission rates ranged from 5.10×10^{12} to $1.42 \times 10^{13} \text{ h}^{-1}$ or 3.66×10^{12} to $1.23 \times 10^{13} \text{ g}^{-1}$ and that the peak diameters varied from 93.1 to 143.3 nm. Airborne particles in the nanometer range (5.6–50 nm), in the ultrafine range (50–100 nm) and in the accumulation mode range (100–560 nm) accounted for 1% to 6%, 16% to 55% and 40% to 60% of the total particle counts, respectively, depending on the brand of incense sticks. To assess the potential health threat due to inhalation of particles released from incense burning, the number of particles of different sizes that can be possibly deposited in the respiratory tract were evaluated for an exposed individual based on known deposition fractions in the literature. The findings indicate that incense smoke may pose adverse health effects depending on exposure duration and intensity.

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1. Introduction

Incense, commonly shaped into sticks, coils and cones, has many diversified uses. It appears to be an integral part of worship of virtually all cultures, ranging from Eastern Chinese Taoist/Buddhist, Indian Hindu and Japanese Shinto temples to Western Christian churches. In addition to religious ceremonial functions, the fragrant smoke released from lighted incense is also intended for aesthetic and therapeutic purposes, and is effective as mosquito

repellents and fresheners. Despite many spiritual and emotional benefits to be gained from burning incense, epidemiological studies have found that individuals who are frequently exposed to incense smoke may be at increased risk for respiratory ailments [1,2]. In fact, its genotoxicity could be comparable to, if not higher than, that of tobacco smoke [3].

The harmful health effects can be attributed to the various contaminants present in incense smoke, including gaseous pollutants, such as carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x) and volatile organic compounds (VOCs) [4–8], and particulate matter (PM) and adsorbed toxic pollutants (polycyclic aromatic hydrocarbons (PAHs) and toxic metals) [4,5,7,9–19]. Unlike toxicants in the vapor phase which have specific chemical composition, airborne particulates vary in sizes

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and composition, both of which are important factors in determining the effects of inhaled particles on human health [20]. In general, particles generated from combustion sources, for instance, incense burning, are submicron in size and contain a host of harmful compounds [21]. Given the extensive applications domain, incense is considered to be a significant source of particles in indoor environments. Therefore, characterization of its emissions is of great value from the health standpoint.

Until now, the bulk of the research on particulates in incense smoke concentrated on determining the time-integrated mass concentrations of total suspended particles (TSP), PM_{10} ($PM \leq 10 \mu m$), $PM_{2.5}$ ($PM \leq 2.5 \mu m$), or size-distributed particles [5,7,11–19]. In contrast, only a few studies measured the real-time size distribution and concentration of particles [4,9,10], an approach deemed to be a better indicator of human exposure due to the variability of emissions in space and time. Presently, there is a dearth of studies investigating the physical characteristics of nanoparticles (NPs, $\leq 0.05 \mu m$) and ultrafine particles (UFPs, $\leq 0.1 \mu m$) present in incense smoke. Both NPs and UFPs possess a greater ability to penetrate the pulmonary interstitium due to their small sizes and interact with the cells, and could thus trigger inflammatory reactions.

In the current work, airborne particles in incense smoke were investigated in a controlled environment by burning various brands of incense sticks usually utilized by the different religious groups, for example, Hindus, Buddhists, Taoists and Shinto followers. The particle number concentration and the size distribution were measured continuously in real time using a high-resolution particle sizer. In addition, the particles emission rates were evaluated because this information would be useful in predicting their number concentration at incense-influenced microenvironments, such as temples and homes, and in assessing the resulting human exposure at these polluted sites.

2. Materials and methods

2.1. Measurements of number concentration and size distribution

To characterize the physical properties of particles in incense smoke, four incense sticks were burned at each of the four corners of a chamber with dimensions 1.016 m (width) \times 0.660 m (depth) \times 1.600 m (height) as illustrated in Fig. 1. The particle emissions were measured using the Model 3091 fast mobility particle sizer spectrometer (FMPS, TSI Incorporated, MN, USA). The aerosol inlet of the FMPS was placed right in middle of the chamber and a small fan stirred air to ensure particle homogeneity within the chamber. FMPS measured sub-micrometer particles in incense smoke over a particle size range of 5.6–560 nm and a particle size resolution of 16 channels per decade, or 32 channels in total, every 1 s.

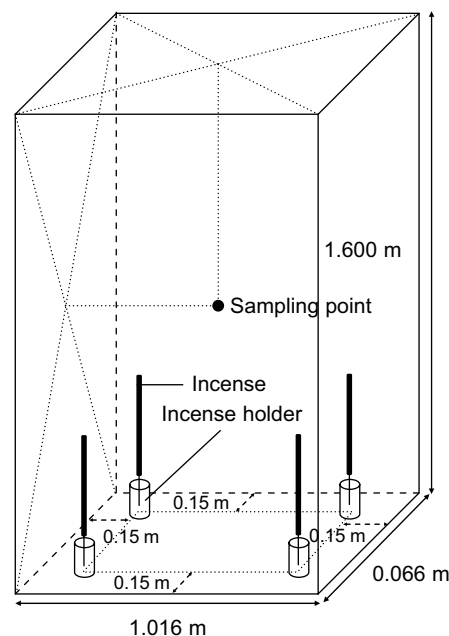


Fig. 1. Experiment apparatus and set-up.

Four popular brands of incense frequently used by the Taoists, Buddhists, Hindus, and Shinto followers were chosen for this study, namely sandalwood-based incense sticks made in India, “smokeless” sandalwood-based incense sticks made in China, aloeswood-based incense sticks made in Taiwan and in Japan. The first three types are produced by coating the incense materials on a supporting bamboo stick, while the last one is a solid stick formed by extrusion and is supposed to burn cleaner than those with internal bamboo cores. The two distinct plant fragrance materials of sandalwood and aloeswood were selected from the many available fragrances because they are most commonly used across many religions.

Prior to measurements, the chamber was purged with laboratory air for about 15 min. Each sampling cycle comprised a 30 min background air monitoring in the chamber, an entire burning cycle, and a 60 min post-burning period. Four incense sticks were lighted with propane lighter outside the chamber for every run before they were brought into the chamber and the door was immediately closed upon keeping the sticks in the respective positions. The experiment was repeated 5 times for each brand of incense sticks. A total of about 7000 to 10 000 data sets were collected for a particular sequence depending on the duration of the burning period.

2.2. Determination of emission rates

The emission rates of particles of different sizes were determined from the number concentration and size distribution data according to the method reported by Liu et al. [22]. This calculation was done on a single-compartment mass balance model assuming that the emission rates and decay rates of the particles remained

constant. Liu et al. [22] used the mass balance model to estimate emission rates of particles based on mass concentrations. However, the model calculation can also be used to estimate the particle emission rate based on number concentration since particles are assumed to be perfect spheres with a constant density. As the airborne particles can be removed by several pathways, for example, dry deposition on the chamber walls, or infiltration through the sampling hole, with different rates for particles of different sizes, their respective removal rates were evaluated using the following equation:

$$C_j = C_{\max,j}[e^{-k_j(t-T)}] \quad \text{for } t \geq T, \quad (1)$$

where C_j (cm^{-3}) represents the number concentration of particles of size j at time t (h), the time elapsed from the initiation of incense smoke, while $C_{\max,j}$ (cm^{-3}) represents the maximum concentration of particles of size j which corresponds to C_j at time T (h), the time when the last incense was burned out. The background concentration of particles, averaged over the 30 min pre-burning interval, was subtracted from the concentration readings to compute C_j and $C_{\max,j}$. The slope of the linear regression plot of $\ln(C_j/C_{\max,j})$ against $(T-t)$ would then be equal to k_j (h^{-1}), the removal rate of particles of size j .

After establishing k_j , the emission rate of particles of size j , P_j (h^{-1}), was subsequently calculated from:

$$C_j = \frac{P_j}{Vk_j}(1 - e^{-k_j t}) \quad \text{for } 0 \leq t \leq T, \quad (2)$$

where V ($1.07 \times 10^{-6} \text{cm}^3$) is the volume of the chamber and P_j is the slope of the linear regression plot of C_j against $(1 - e^{-k_j t})/Vk_j$. The emission rate of particles of size j in terms of per mass of incense burned, E_j (g^{-1}), was then evaluated from the burn rate, B (g h^{-1}), where m_i and m_f are the masses of the incense before and after burning, respectively, from

$$B = \frac{m_i - m_f}{T}, \quad (3)$$

$$E_j = \frac{P_j}{B}. \quad (4)$$

2.3. Particle deposition in the lung

One of the most important parameters in the evaluation of potential health impacts based solely on physical characteristics is the amount of particles that can be deposited in the lung, which is mainly governed by the particle diameter (D_p , nm). For airborne particles of aerodynamic diameter ranging from 5.6 to 560 nm, almost all particles deposited in the respiratory tract would be deposited in the alveolar region as demonstrated by Heyder et al. [23]. These authors experimentally determined both total and regional deposition data for mono-disperse aerosols of fixed diameters. In order to estimate the deposition fraction of different sized particles measured

in this study, a continuous function relating deposition fraction with particle diameter is needed. Based on this consideration, the following equations (5)–(7) were derived using the mean experimental values of the total deposition fraction of 5–700 nm particles in three healthy human subjects with different breathing patterns as reported by Heyder et al. [23]. A software, FindGraph (UNIPHIZ Lab), was employed for curve fitting and the best-fit function was found to be

$$f_j = 0.8550 - \frac{2.991Dp_j}{178.1 + Dp_j} + \frac{3.112Dp_j}{525.7 + Dp_j} \quad (\text{standard error} = 0.02102), \quad (5)$$

$$N = \sum_{\text{all } j} N_j = \sum_{\text{all } j} P_j \times f_j, \quad (6)$$

$$f = \frac{N}{P}, \quad (7)$$

where f_j and f denote the deposition fraction of particles of size j and that of all particles from 5.6 to 560 nm, respectively. N_j (h^{-1}) and N (h^{-1}) represent the number of particles of size j and that of all particles from 5.6 to 560 nm that can be deposited in the lung, respectively. P_j has the same meaning as explained above, and P (h^{-1}) is the total emission rate of particles with diameter, 5.6–560 nm. The above equations assume that all particles contained in incense smoke are inhaled in.

3. Results and discussion

3.1. Temporal variation of number concentration and size distribution

The temporal variation of the total number concentration of particles for a typical sampling sequence is shown in Fig. 2. It consists of a 30-min background measurement ($t < 0$), the burning period ($0 \leq t \leq T$), and a 60-min post-burning period ($t \geq T$). It should be noted that the burning duration is dependent on the brands of incense sticks used. The relevant details of the incense sticks and the combustion experiment, including the initial length (l_i), final length (l_f , length of the bamboo stick left after burning, initial mass (m_i), final mass (m_f ; again, $m_f = 0$ for Japanese incense), burning duration (T) and burn rate (B) are given in Table 1; in the case of the Japanese aloeswood incense stick the l_f is zero since there was no internal bamboo core.

From Fig. 2, it can be seen that the total number concentration of particles was essentially constant with an average of $4.92 \times 10^4 \text{cm}^{-3}$ in the absence of any incense smoke. As soon as the four lighted incense sticks were brought into the experimental chamber at $t = 0$, the number concentration increased rapidly until the last incense stick burned out at $t = T$. The maximum number concentration, C_{\max} , was reached at time T . Subsequently, the particle decay was observed with the concentration falling back to the original background level approximately

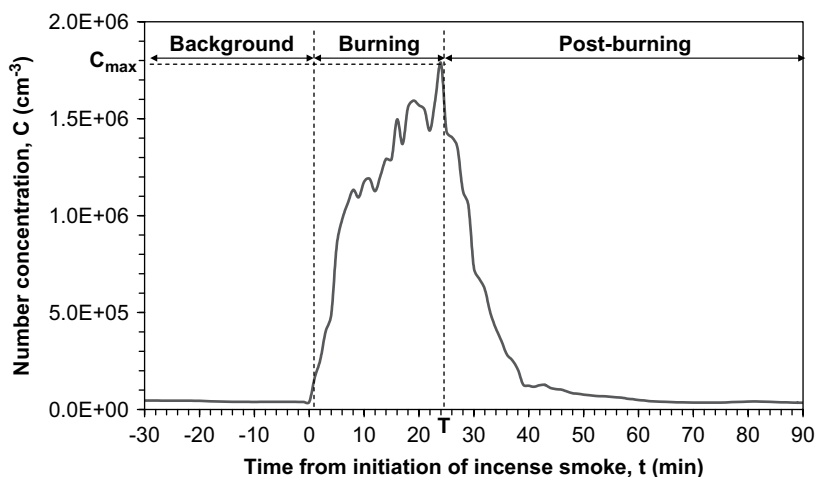


Fig. 2. Temporal variation of number concentration of a typical sampling cycle.

Table 1
Characteristics of different brands of incense

Type of incense	l_i (cm)	l_f (cm)	m_i (g)	m_f (g)	T (h)	B (g h ⁻¹)
Indian sandalwood	25.0±0.2	7.6±1.2	0.9092±0.0806	0.1364±0.0328	46±2	1.06±0.10
Smokeless sandalwood	34.0±0.2	11.2±0.3	1.2434±0.0779	0.1580±0.0229	47±2	1.38±0.07
Taiwanese aloeswood	36.7±0.1	11.0±0.4	1.2602±0.0672	0.1760±0.0270	63±2	1.04±0.05
Japanese aloeswood	14.1±0.0	0	0.4444±0.0023	0	27±1	1.00±0.02

40 min later. The average C_{\max} concentration was $2.42 \times 10^6 \text{ cm}^{-3}$ for Indian sandalwood incense sticks, $1.11 \times 10^6 \text{ cm}^{-3}$ for Chinese smokeless sandalwood incense sticks, $1.40 \times 10^6 \text{ cm}^{-3}$ for Taiwanese aloeswood incense sticks and $1.64 \times 10^6 \text{ cm}^{-3}$ for Japanese aloeswood incense sticks. This observation indicates that four lighted incense sticks can cause the number concentration to increase by a factor of 20 to 50 in a closed chamber of 1.07 m^3 .

It should be noted that in the computation of the removal rate of particles of size j , k_j , the number concentration of particles of size j at $t = T$ was used. This is conceivable since the particle size distribution did not shift throughout the burning period as demonstrated by Fig. 3. The maximum concentration was reached for all particle sizes at time, T . Fig. 3 presents the normalized number concentration, $dN/d \log D_p$, of particles of different diameters (D_p) at various stages of the burning period, including start ($0 < t \leq T/3$), middle ($T/3 < t \leq 2T/3$), and end ($2T/3 < t \leq T$). The key reason for the peak diameters not to shift in-between measurements is that the relative humidity in the chamber was maintained at around 40%. At this low level, the hygroscopic growth of particles is insignificant [24].

It is indeed interesting to note, from visual inspection of the graph, that different brands of incense sticks show distinct modal diameters and that they appear to be independent of the main ingredient used. The peak diameter ranged from 93.1 nm for Chinese smokeless sandalwood and Japanese aloeswood incense sticks to

124.1 nm for Indian sandalwood incense sticks to 143.3 nm for Taiwanese aloeswood incense sticks. These values are comparable to the peak diameter of about $0.1 \mu\text{m}$ discovered by Li et al. [9] for both mosquito coil and joss sticks burning. The differences could be related to the fineness of milled plant materials in incense sticks. To support this hypothesis, whole incense sticks were subjected to JSM-5600LV scanning electron microscope (SEM, JEOL Ltd, Tokyo, Japan). The scanning electron micrographs of the four different incense sticks in Fig. 4 indeed revealed that the incense powder of the Chinese smokeless sandalwood incense sticks are fine while the Taiwanese aloeswood incense sticks are made of coarser materials. Ninomiya et al. [25] also found that the fuel size influences the size of particles produced during combustion, but the study investigated airborne particles in the super-micrometer range ($> 1 \mu\text{m}$).

3.2. Emission rates of different brands of incense

As discussed earlier, the emission rates of size-distributed particles from different brands of incense sticks on an hourly as well as on mass basis were determined using Eqs. (2)–(4) after taking into account the removal rates of particles of different sizes from Eq. (1). The two stacked column charts of Fig. 5 show the number of NPs (5.6–50 nm), UFPs (50–100 nm) and accumulation mode particles (100–560 nm) that were emitted per hour and per mass of incense sticks burned. The error bars represent the

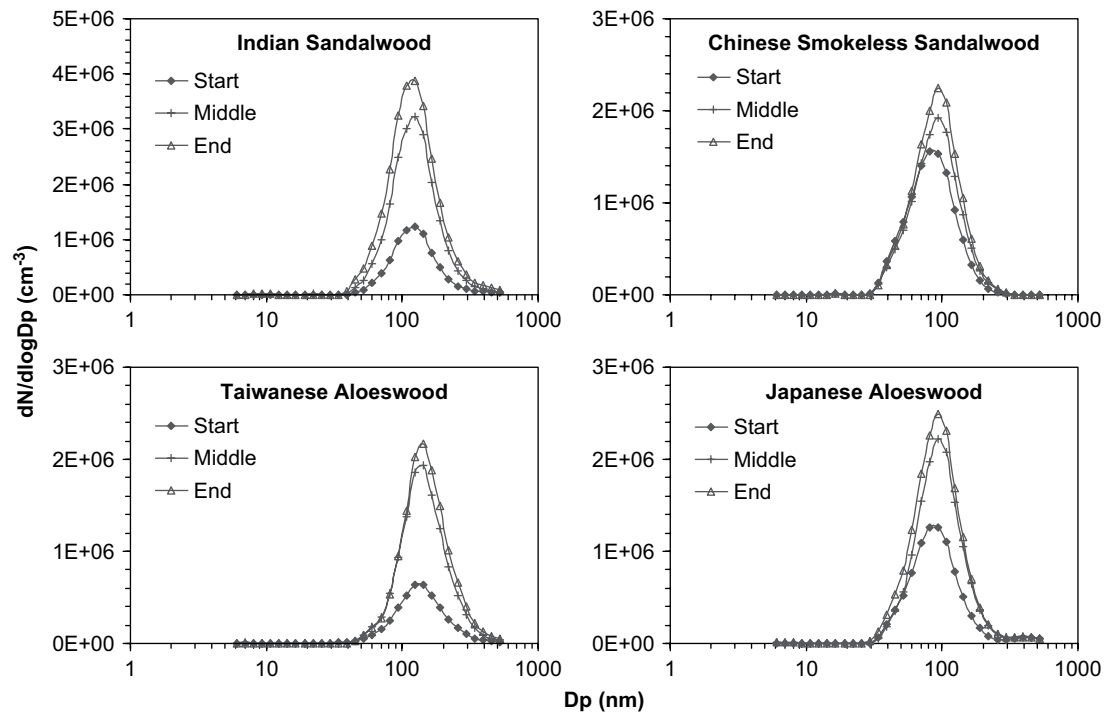


Fig. 3. Particle size distribution at different stages of the burning process.

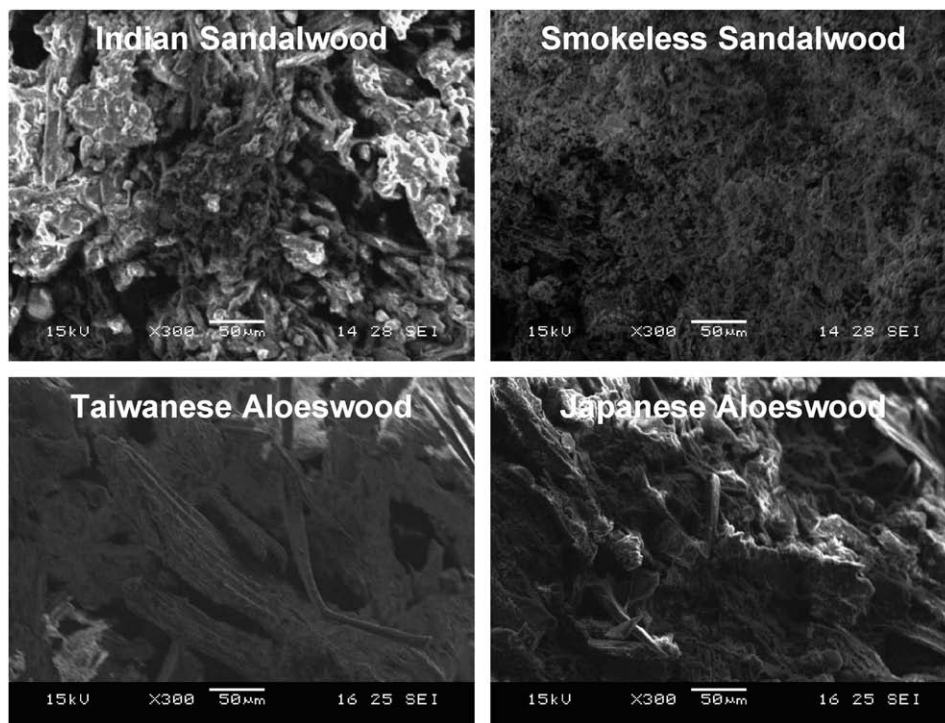


Fig. 4. Scanning electron micrographs of different brands of incense.

standard deviation associated with the total emission rate of 5.6–560 nm particles resulting from the five replicate measurements.

From both units, Indian sandalwood incense sticks emitted particles with the largest rate, $1.42 \times 10^{13} \text{ h}^{-1}$ or $1.23 \times 10^{13} \text{ g}^{-1}$, followed by Japanese aloeswood incense

sticks with $7.11 \times 10^{12} \text{ h}^{-1}$ or $7.21 \times 10^{12} \text{ g}^{-1}$, Taiwanese aloeswood incense sticks with $6.49 \times 10^{12} \text{ h}^{-1}$ or $6.31 \times 10^{12} \text{ g}^{-1}$ and Chinese smokeless sandalwood incense sticks with $5.10 \times 10^{12} \text{ h}^{-1}$ or $3.66 \times 10^{12} \text{ g}^{-1}$. Overall, the emission rates of particles from incense sticks can be said to be in the region of 10^{12} – 10^{13} h^{-1} or g^{-1} . Table 2 compares

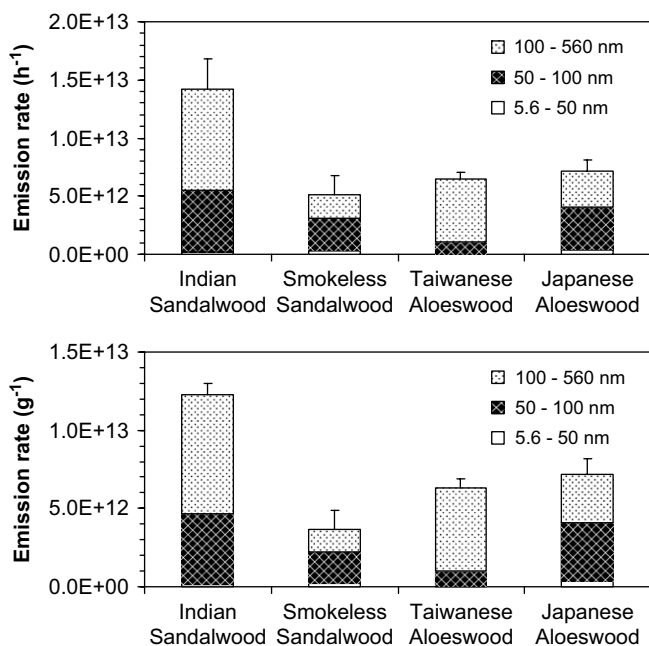


Fig. 5. Emission rates of particles for different brands of incense.

the emission rates of particles from different indoor sources as determined by He et al. [26] and Ashari et al. [27]. It is found that burning just one incense stick is comparable to a number of indoor sources that are known to be strong emitters of particles, such as smoking and cooking.

In view of the fact that incense is usually only known by their main ingredient, for example sandalwood and aloeswood, and the type and amount of other ingredients are a closely guarded secret, the differences in particulate emissions between various brands of incense sticks can only be hypothesized based on our general understanding of incense made from different materials and from different countries. Another problem is that there are no quality standards. Each tree grows in its own unique natural environment, absorbing the minerals and other nourishments from the ground.

To the best of our knowledge, the combustion of aloeswood, regarded as one of the finest aromatic woods, tends to emit less smoke than sandalwood. This could be one reason why Indian sandalwood incense sticks produced much more particles than either Taiwanese or Japanese aloeswood incense sticks. Chinese smokeless incense sticks are not considered in this comparison as they are touted to be smokeless. From the controlled experiments carried out in this study, this appears to be indeed the case; they generated relatively much less particles than others.

Another factor for the higher emission factor of Indian sandalwood incense sticks could lie in the amount of ingredients used. Indian incense usually smells stronger than Chinese, Taiwanese, or Japanese incense, which means that it is highly probable that a larger quantity of fragrances is added to achieve their perfume-like smell and combusting more of these materials led to increased

emissions of particles. This could also be the explanation for the higher emission rate of Japanese aloeswood incense sticks as compared to Taiwanese aloeswood incense sticks. The Japanese incense incorporates some lavender extracts, one of the most commonly used essence in aromatherapy, and is artificially colored navy blue. The additional essential oil and colorant could have been the cause of elevated particulate emissions.

Even though Indian sandalwood incense sticks released roughly 2 to 3 times more particles than the other types of incense sticks studied, it cannot simply be concluded that the former types are more harmful to human health without looking at the size-resolved emission rates which determine particle deposition in the human respiratory tract. From Fig. 5, it can be seen that majority of the particles lie in the ultrafine and accumulation mode range (99%), with only a tiny proportion in the nanometer range (1%). In contrast, Chinese smokeless sandalwood incense sticks, though low in total emissions, comprise the highest percentage of NPs at 6% compared to other brands of incense sticks.

A fair assessment of the potential health impacts on exposure to different kinds of incense smoke would then be the actual amount of particles which can be deposited in the respiratory tract of an individual who is exposed to incense smoke for one whole hour, with one incense stick burning at a time. As evaluated from Eqs. (5)–(7), smoke from the Indian sandalwood incense stick remained at alarming levels with around 3.76×10^{12} particles (26.5% of total particulate emissions) deposited in the alveolar region in an hour, followed by Japanese aloeswood incense stick ($N = 2.12 \times 10^{12} \text{ h}^{-1}$, $f = 29.8\%$). However, exposure to Chinese smokeless sandalwood incense smoke can lead to a larger amount of particles being deposited in the human lung ($N = 1.57 \times 10^{12} \text{ h}^{-1}$, $f = 30.9\%$) compared to Taiwanese aloeswood incense smoke ($N = 1.31 \times 10^{12} \text{ h}^{-1}$, $f = 20.2\%$) due to the much higher percentage of UFPs and NPs present in their emissions (60.7% against 16.3%).

Such a large number of deposited particles can result in particle overload which will in turn lead to acute inflammation and impairment of alveolar macrophage-mediated lung clearance. This vicious cycle is likely to continue as more particles are accumulated due to retarded particle clearance, which could eventually result in lung tumor following a sequence of pulmonary events [28]. Von Klot et al. [29] found cardiac readmissions increased with the number concentration at a rate ratio of 1.026 per 10^4 cm^{-3} . Therefore, exposure to incense smoke is of health concern, and should be reduced as much as possible. If unavoidable, incense should be burned in a well-ventilated setting so as to decrease the number concentration and lessen the potential health impacts.

4. Conclusions

Physical characterization of the number concentration and size distribution of sub-micron particles from 5.6 to

Table 2
Comparisons of particle emission rates from different indoor sources

Source	Size range (μm)	Emission rate (10^{11} min^{-1})	Reference
Indoor sources			
Incense and candles			
Incense sticks	0.0056–0.56	0.85–2.37	This study
Candle vapor eucalypt oil	0.007–0.808	5.52	[26]
Scented candles	0.02–0.1	0.88	[27]
Pure wax candles	0.02–0.1	3.65	[27]
Air freshener spray	0.02–0.1	2.34	[27]
Cigarette smoking	0.007–0.808	1.91	[26]
	0.02–0.1	3.76	[27]
Cooking			
Gas stove	0.007–0.808	7.33	[26]
Gas stove	0.02–0.1	1.30	[27]
Electric stove	0.02–0.1	6.8	[27]
Kettle	0.007–0.808	0.35	[26]
Microwave	0.007–0.808	0.55	[26]
Oven	0.007–0.808	1.27	[26]
Toasting	0.007–0.808	6.75	[26]
Cooking	0.007–0.808	5.67	[26]
Cooking pizza	0.007–0.808	1.65	[26]
Grilling	0.007–0.808	7.34	[26]
Frying	0.007–0.808	4.75	[26]
Frying meat	0.02–0.1	8.27	[27]
Heating			
Hair dryer	0.007–0.808	0.11	[26]
Fan heater	0.007–0.808	4.07	[26]
Electric air heater	0.02–0.1	3.89	[27]
Radiator	0.02–0.1	8.84	[27]
Ironing			
Flat iron (without steam) on a cotton sheet	0.02–0.1	0.007	[27]
Flat iron (with steam) on a cotton sheet	0.02–0.1	0.06	[27]
Cleaning			
Sweeping	0.007–0.808	0.12	[26]
Vacuuming	0.007–0.808	0.97	[26]
Vacuum cleaner with full bag	0.02–0.1	0.35	[27]
Vacuum cleaner (motor) without bag	0.02–0.1	0.38	[27]
Washing machine	0.007–0.808	0.15	[26]
Washing	0.007–0.808	0.96	[26]
Shower	0.007–0.808	0.78	[26]

560 nm was carried out, for the first time, for different brands of incense commonly used by various religious groups. The four types of incense sticks investigated were Indian sandalwood incense sticks, Chinese sandalwood incense sticks (claimed to be “smokeless”), Taiwanese aloeswood incense sticks and lastly, Japanese aloeswood incense sticks. Based on size-resolved, single-compartment model, particulate emission rates from various incense burning, including ultrafine and nanoparticles, were evaluated. Furthermore, comparisons were also made between the four different brands of incense under study and deposition fractions of particles in the lungs were determined for exposure and risk assessment.

In general, combustion of Indian sandalwood incense stick emits the most number of 5.6–560 nm particles per

hour and per gram of incense burned, followed by Japanese aloeswood incense sticks, Taiwanese aloeswood incense sticks and Chinese “smokeless” sandalwood incense sticks. However, if the particle size distribution is taken into account, the Taiwanese aloeswood incense sticks are “cleaner” because bigger accumulation mode particles with relatively lower deposition rate were produced. On the whole, continuous and prolonged exposure to incense smoke is of concern due to the high particle number emission rates.

Future work will involve a series of comprehensive chemical characterization and biological tests to determine the mass concentrations of toxins and mutagens, and toxicity of size-distributed particles released from incense burning to make a better assessment of public health outcomes due to exposure.

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