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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 $5.10 \times 10^{12}$ to $1.42 \times 10^{13}\,h^{-1}$ or $3.66 \times 10^{12}$ to $1.23 \times 10^{13}\,g^{-1}$ 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.


*Keywords:* Incense; Emission rate; Nanoparticles; Ultrafine particles; Particulate matter; Size distribution; Number concentration; Combustion; Indoor air quality; Fast mobility particle sizer (FMPS)

## 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), $PM_{10}$ ($PM \leqslant 10\,\mu m$), $PM_{2.5}$ ($PM \leqslant 2.5\,\mu m$), 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, $\leqslant 0.05\,\mu m$) and ultrafine particles (UFPs, $\leqslant 0.1\,\mu m$) 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) × 0.660 m (depth) × 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.

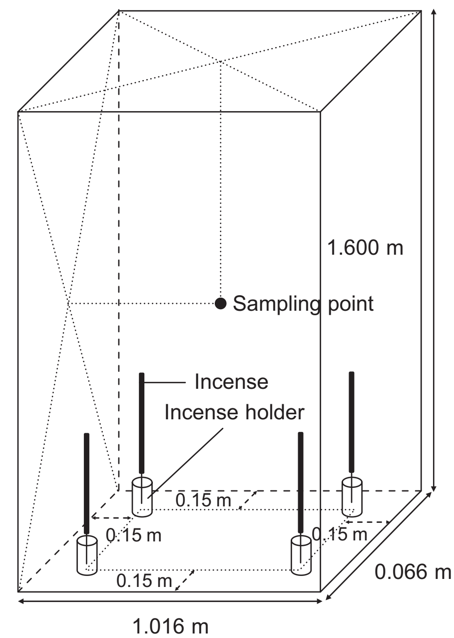


Fig. 1. Experiment apparatus and set-up.

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