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Characterization of Gas and Particle Emission from Smoldering Incenses with Various Diameters

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As a common religious ritual in Chinese society, burning incense sticks causes air pollution and is related to the occurrence of lung cancer (MacLennan et al. 1977), childhood leukemia (Lowergard et al. 1987) and brain tumors (Preston-Martin et al. 1982). The Ames test has demonstrated the mutagenic effect of incense smoke (Sato et al. 1980; Rasmussen et al. 1987; Chang et al. 1997).

Incense is burned in a smoldering state, subsequently producing incense smoke that contains gas and particulates. The gas phase consists of carbon monoxide (Jetter et al. 2002), carbon dioxide (Yang and Lin, 2005), nitrogen oxides, formaldehyde, volatile organic compounds (VOCs) and so on. The particulate phase contains almost exclusively of pure particulates (Cheng et al. 1995), but to these particulates may be bound semi-volatile organic compounds (Schoental et al. 1967; Lin and Wang, 1994; Lin and Tang, 1994; Lin and Lee, 1998). The particulates tend to be in the submicron range, and include ultrafine particles ~~with~~ that are smaller than 100 nm. Ultrafine particles that are deposited in human alveoli are likely to increase cellular oxidative stress and inflammatory responses (Dick et al. 2003).

The characteristics of incense smoke may vary with the constituents of the incense stick and the conditions of combustion (airflow, temperature, humidity and oxygen content). This study elucidates how temperature affects the yields of pollutants from smoldering incense.

MATERIALS AND METHODS

This study focused on a brand of less-smoke incense prepared by a local manufacturer. Incense sticks with diameters of 3, 3.75, and 5 mm were used. Their ingredients were unknown, but carbon, hydrogen and nitrogen contents were identified using an elemental analyzer (2400 CHN Elemental Analyzer, Perkin-Elmer, U.S.A.). The heat value of each incense was measured using an oxygen bomb calorimeter (1271 Oxygen Bomb Calorimeter, Parr Instrument Company, U.S.A.).

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An incense stick was burned in a combustion system, which has been in detail elsewhere (Yang and Lin, 2005). An incense stick was ignited and burnt at flow rate of 5 L/min. The surface temperature of the burning tip of incense was measured using a K-type thermocouple made of 79 μm nickel-aluminum and nickel-chrome wires. The incense smoke was led into a 7.3 L test chamber. Particles were counted and their sizes measured using a Scanning Mobility Particle Sizer (SMPS, Model 3936, TSI Inc., USA), which coupled a differential mobility analyzer (DMA, Model 3080, TSI Inc.) with a condensation particle counter (CPC, Model 3022, TSI Inc.). All particles were sampled using a quartz filter (37 mm, Pallgelman, U.S.A.) in a two-piece cassette holder at flow rate of 2 L/min for ten minutes to determine their concentration. The incense smoke was diluted with pure nitrogen (99.99 %, Shen Yi Gas Co., Taiwan) before it entered a 1.4 L dilution chamber to measure the concentrations of carbon monoxide and carbon dioxide. This step fitted the concentration of pollutants into the specified detectable ranges of 0-5000 ppm for CO_2 and 0-500 ppm for CO, which were set for the Q-Trak™ Indoor Air Quality Monitor (Model 8550/8551, TSI Inc., U.S.A.), which measured the CO_2 and CO concentrations with an accuracy of ±3 %. The ppbRAE Portable VOC Monitor (RAE SYSTEMS Inc., USA) with UV at 10.6 eV measured a total VOC of 0-200 ppm with an accuracy of ±10 %. Zero calibration and span calibration were for each monitoring instrument using a reference compound (CO_2, CO or isobutylene) of known concentration, by following the manufacturer's instructions. Standard isobutylene (10 ppm, RAE SYSTEMS Inc., USA) was adopted to calibrate the VOC Monitor. Before and after burning, an individual joss stick was weighed and so that the net loss of mass and the rate of burning of incense could be determined.

The emission rates and emission factors of particles (or gaseous) were derived from the following equation, which is based on the conservation of mass.

$$V \times \frac{dCi}{dt} = R \times E_f - Q \times Ci \qquad (1)$$

where V (m^3) is the volume of the test chamber; C_i (mg/m^3 or particles/cm^3) is the concentration of gas or particles at a given time; R (g/hr) is the incense-burning rate; E_f (mg/g or particles/g) is the emission factor of each pollutant, and Q (5 L/min) is the air flow rate. $dCi/dt=0$ when generation and removal are in dynamic equilibrium. Equation 1 is then rewritten as follows.

$$E_f = \frac{Q \times C}{R} \qquad (2)$$

In Eq. 2, the emission rate is defined as: Q × C, which is the flow rate multiplied by the equilibrium concentration of the pollutant. Then, the emission factor, E_f, can be thought of as the specific emission rate normalized to the incense burning rate. The expression for the concentrations of gaseous pollutants was converted from ppm (v/v at 25℃, 1 atm.) to mg/m^3 based on the ideal gas law. In this conversion, the molecular weight of the total VOCs was set to 92 g, as a toluene equivalent.

RESULTS AND DISCUSSION

The heating value of the incense was 5060 Kcal/Kg. The weight percentages of carbon, hydrogen, nitrogen, ash and water in the incense were 61.96, 2.62, 0.70, 12.28 and 5.86 %, respectively. The burning tips of an incense cone with heights from 13.5 to 25 mm varied as the diameter increased. Along with the increment of diameter, the average surface temperature at the burning tip changed from 368.0 °C (n=3, CV=0.02), 395.8 °C (n=3, CV=0.04) to 450.1 °C (n=3, CV=0.04). Additionally, the burning rate increased from 1.67 g/hr (n=3, CV=0.02), 2.19 g/hr (n=3, CV=0.06) to 3.3 g/hr (n=3, CV=0.07)(Fig. 1). The burning tip appeared brighter as the diameter increased from 3 mm to 5 mm. Since the surface areas of the incense burning tips increased with diameters, oxygen became more available to the surface of the burning tip, promoting the combustion of char as well as the release heat. Therefore, the heat increased both the incense burning rate and the surface temperature of the incense burning tip.

Figure 2 plots the size distribution of particulates from burning the three incenses at a flow rate of 5 L/min. The number concentrations of particles of size 88.2~914 nm increased with diameter of the incense as the particles were grouped by size in increments of 0.7 nm (n=6, F=2.74~7.37, $F_{0.1}(2, 15) = 2.7$). However, the number concentrations of particles of size 18.1~88.2 nm did not differ significantly with diameter of incense (n=6, F=0.17~2.3, $F_{0.1}(2, 15) = 2.7$). The sizes of particulates from burning incense tend increase as the diameter of the incense increases. The yield of low volatile vapors and particulates at the beginning of incense burning likely depends on the incense diameter. Incense with a large diameter seems to produce a larger quantity of low-volatile organic compounds as well as particles than one with a smaller diameter. The low volatile materials might condense or adsorb on the surface of primary combustion particles. Moreover, the coagulation of primary combustion particles may ultimately increase the particle size.

In fact, the Fig. 3 shows that the particle concentration (number, volume or mass) increased linearly with the diameter of the incense. The emission rate, which is the product of the concentration and the air flow rate of 5 L/min, varied similarly. However, the emission factor was correlated inversely with the incense diameter. The particle number emission rates and factors from smoldering incenses with various incense diameters ranged from 3.85×10^{12} #/hr (n=6, CV=0.02) to 4.32×10^{12} #/hr (n=6, CV=0.01) and from 2.28×10^{12} #/g (n=6, CV=0.03) to 1.36×10^{12} #/g (n=6, CV=0.02), respectively. The volume emission rates and factors ranged from 5.05×10^{18} nm^3/hr (n=6, CV=0.03) to 6.97×10^{18} nm^3/hr (n=6, CV=0.04) and 2.99×10^{18} nm^3/g (n=6, CV=0.06) to 2.19×10^{18} nm^3/g (n=6, CV=0.06), respectively. The mass emission rates and factors ranged from 8.6 mg/hr (n=3, CV=0.04) to 9.2 mg/hr (n=3, CV=0.04) and from 5.1 mg/g (n=3, CV=0.04) to 2.9 mg/g (n=3, CV=0.04), respectively. These mass emission rates and factors differed from those determined by Lee et al. Lee et al. (2004) they characterized the emissions from traditional incenses in a large environmental chamber. The emission rates of

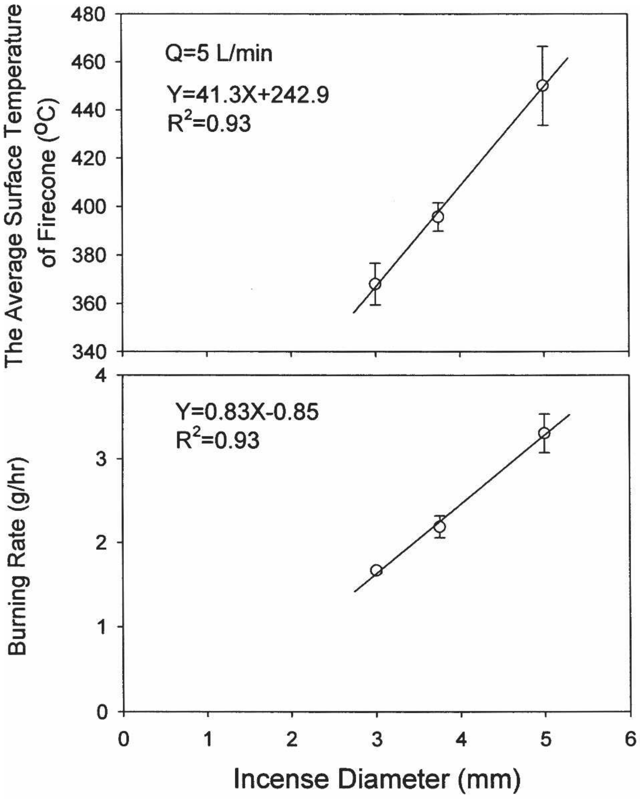

Figure 1. Comparison of burning rates and the average surface temperature of incense tips from smoldering incenses with various diameters (Bar: mean ± standard deviation).

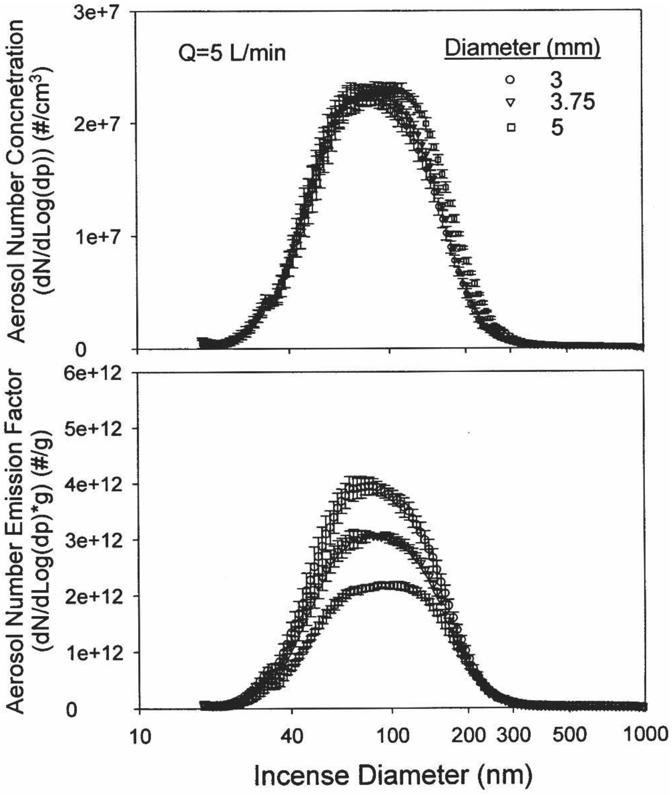

Figure 2. Aerosol number concentrations and emission factors versus particle sizes from smoldering incenses with various diameters (Bar: mean ± standard deviation).

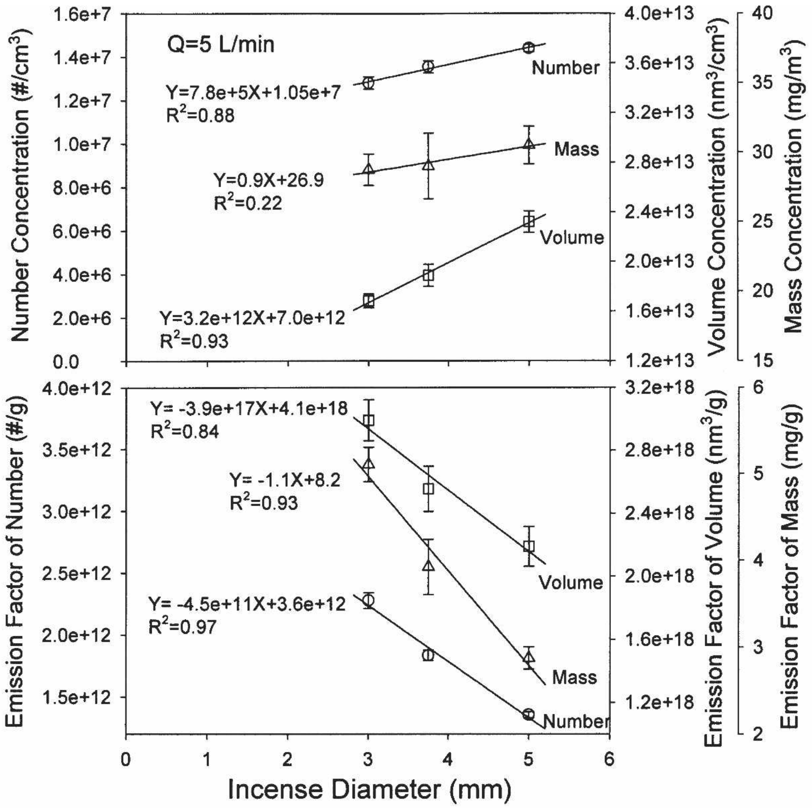

Figure 3. Comparison of aerosol numbers, volume, mass concentrations, and emission factors from smoldering incenses with various diameters (Bar: mean ± standard deviation).

PM2.5 were 28.4~372.6 mg/hr, and the emission factor was 104~9.6 mg/g. The results probably differed from those herein because each study used different incense and combustion conditions.

The concentrations of CO_2, CO and TVOCs, and their emission rate consistently increased with temperature from 368.0 to 450.1 °C as incense of various diameters was burned (Fig. 4). The linear regression models for the emission rates of CO_2, CO and TVOCs versus incense diameter were y=1003.8x-682.1 (R^2=1.00), y=414.2x-385.8 (R^2=1.00) and y=58.0x-50.1 (R^2=0.98), respectively. The CO_2 emission rates of incense ranged from 2322.0 mg/hr (n=3, CV=0.03) to 4332.6 mg/hr (n=3, CV=0.01). The CO emission rates were from 845.9 mg/hr (n=3, CV=0.02) to 1684.0 mg/hr (n=3, CV=0.002). The TVOCs emission rates ranged from 13.0 mg/hr (n=3, CV=0.05) to 24.4 mg/hr (n=3, CV=0.02). However, the emission factors of CO_2, CO or TVOCs were not significantly correlated with incense diameter. The CO_2 emission factors of the

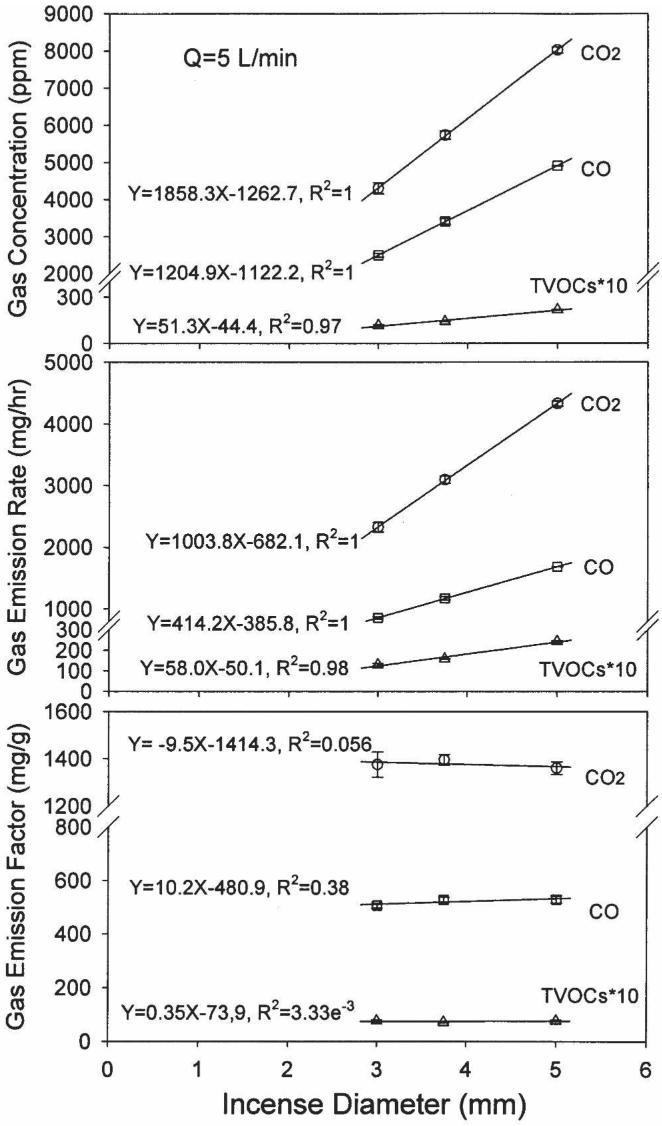

Figure 4. Comparison of CO_2, CO, and TVOCs emission concentrations and corresponding emission factors from smoldering incenses with various diameters (Bar: mean ± standard deviation).

incenses ranged from 1360.6 mg/g (n=3, CV=0.02) to 1375.5 mg/g (n=3, CV=0.04). The range of CO emission factors was 506.3 mg/g (n=3, CV=0.02) to 528.9 mg/g (n=3, CV=0.02). The range of TVOCs emission factors was from 7.1 mg/g (n=3, CV=0.06) to 7.7 mg/g (n=3, CV=0.04).

However, the combustion efficiency ((CO_2)/(CO+CO_2)), based on the CO and

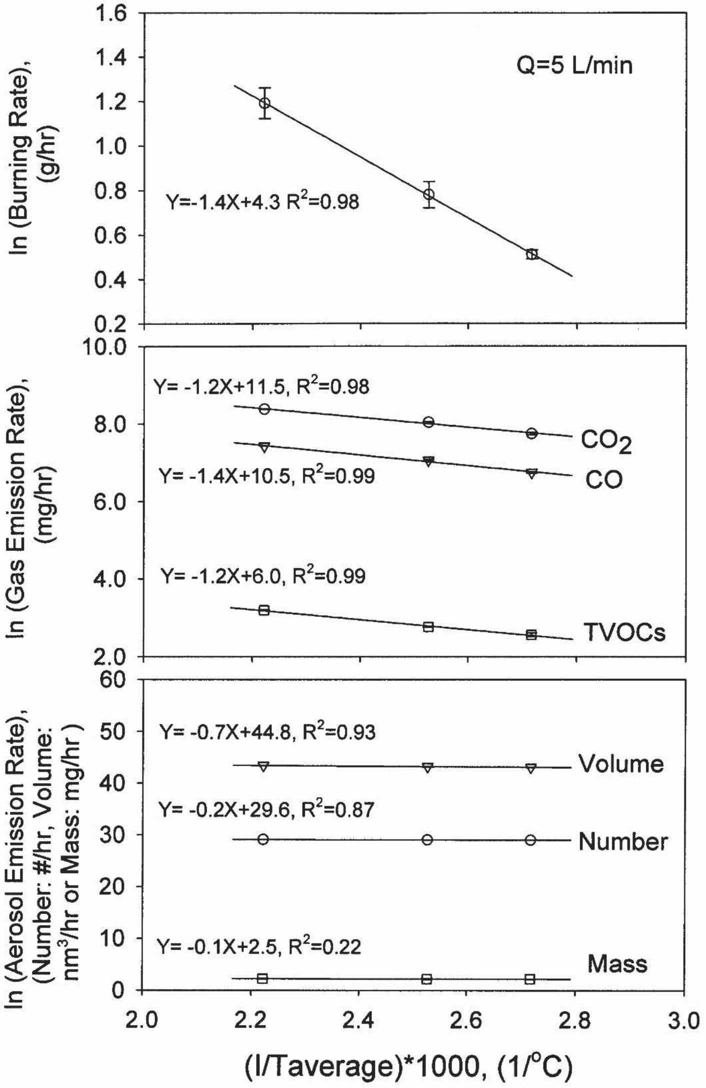

Figure 5. The plots of incense burning rate, gas, and particle emission rates versus $(1/T_{average})*1000$ from smoldering incenses (Bar: mean ± standard deviation).

CO_2 concentrations, ranged from 0.63 (n=3, CV=0.007) to 0.62 (n=3, CV=0.003), and was negative correlating with incense diameter ($y=-6.19x+0.65$, $R^2=0.80$), indicating that combustion was relatively incomplete in the smoldering of coarse incenses.

The Arrhenius plot presented in Fig. 5 demonstrates that the emission rate of CO_2, CO, TVOCs or particles is mainly associated with the temperature, which depends on the diameter of the incense. Thus, the smoldering incense at the lowest burning tip temperature produced the least amount of gaseous and particulate pollutants.

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