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AIR POLLUTANT EMISSIONS FROM THE BURNING OF INCENSE, MOSQUITO COILS, AND CANDLES IN A SMALL EXPERIMENTAL CHAMBER

การปลดปล่อยมลพิษอากาศจากการเผาไหม้ธูป ยากันยุง และเทียนไขในห้องทดสอบขนาดเล็ก

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Abstract

Combustion of incense, candles, and mosquito coils produces a variety of air pollutants, which may cause adverse health effects. This study was to characterize emissions of particulate matter ($PM_{2.5}$) and carbon monoxide (CO) from the burning process of three selected types of emitters: incense, candles, and mosquito coils. The experiments were conducted in an aluminum foil-lined wall chamber with a dimension of 1x1x1 m^3. Emission rates and emission factors of the test emitters were obtained from fitting time-dependent concentrations of the measured pollutants to a single-compartment mass balance model. The emission rates and emission factors of incense combustion were: $PM_{2.5}$ 154-255 mg/h and 65.6-252 mg/g; CO 378-790 mg/h and 242-454 mg/g. The emission rates and emission factors of mosquito coil combustion were: $PM_{2.5}$ 266-1611 mg/h and 112-184 mg/g; CO 722-837 mg/h and 82.4-368 mg/g. The emission rates and emission factors of candle combustion were: $PM_{2.5}$ 8.80-9.97 mg/h and 1.87-2.17 mg/g; CO 74.7-76.8 mg/h and 14.2-18.4 mg/g. The emission rates and emission factors of $PM_{2.5}$ and CO for the test incense and mosquito coils were of similar magnitude, but they were approximately 1-2 orders of magnitude higher than those for the test candles. The reason could be due to the fact that incense and mosquito coils are produced purposely to combust incompletely for a smoldering effect. The simulation for the impacts of burning of the combustible household products on occupant exposure shows that the increased ventilation rate of a room is suggested to reduce health risks of customers exposed to the released air pollutants.

Keywords: particulate matter, carbon monoxide, emission rate, emission factor, incense, mosquito coil, candle

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บทคัดย่อ

การเผาไหม้ธูป เทียน และยากันยุง ก่อให้เกิดสารมลพิษอากาศหลายประเภท ซึ่งอาจเป็นอันตรายต่อสุขภาพได้ งานวิจัยนี้ศึกษาการปลดปล่อยสารมลพิษอากาศ ได้แก่ ฝุ่นขนาดเล็กกว่า 2.5 ไมโครเมตร ($PM_{2.5}$) และก๊าซคาร์บอนมอนอกไซด์ (CO) จากการเผาไหม้ธูป เทียน และยากันยุง อย่างละ 3 ยี่ห้อ โดยทำการทดลองในห้องทดสอบที่มีพื้นผิวภายในบุด้วยอลูมิเนียมฟอยล์ ขนาดห้อง 1x1x1 ลบ.ม. การคำนวณหาค่าอัตราการปลดปล่อยสารมลพิษ (Emission rate) และค่าตัวคูณการปลดปล่อยสารมลพิษ (Emission factor) ใช้การพยากรณ์ด้วยการวิเคราะห์การถดถอยแบบไม่เป็นเชิงเส้นตรง (Non linear regression analysis) โดยใช้ข้อมูลความเข้มข้นสารมลพิษที่วัดได้ตามเวลาที่ผ่านไปและแบบจำลองทางคณิตศาสตร์ของสมดุลมวลสารมลพิษในอากาศภายในห้องทดสอบ ผลการศึกษา พบว่า ค่าอัตราการปลดปล่อยสารมลพิษและตัวคูณการปลดปล่อยสารมลพิษของการเผาไหม้ผลิตภัณฑ์ทั้งสามชนิด มีดังนี้ ธูปทำให้เกิดฝุ่นขนาดเล็ก 154-255 มก./ชม. และ 65.6-252 มก./ก. ของธูปที่เผาไหม้ และเกิดคาร์บอนมอนอกไซด์ 378-790 มก./ชม. และ 242-454 มก./ก. ของธูปที่เผาไหม้, การเผาไหม้ยากันยุงทำให้เกิดฝุ่นขนาดเล็ก 266-1611 มก./ชม. และ 112-184 มก./ก. ของยากันยุงที่เผาไหม้ และเกิดคาร์บอนมอนอกไซด์ 722-837 มก./ชม. และ 82.4-368 มก./ก. ของยากันยุงที่เผาไหม้, การเผาไหม้เทียนไขทำให้เกิดฝุ่นขนาดเล็ก 8.80-9.97 มก./ชม. และ 1.87-2.17 มก./ก. ของเทียนไขที่เผาไหม้ และเกิดคาร์บอนมอนอกไซด์ 74.7-76.8 มก./ชม. และ 14.2-18.4 มก./ก. ของเทียนไขที่เผาไหม้ ทั้งนี้ ค่าอัตราการปลดปล่อยสารมลพิษและตัวคูณการปลดปล่อยสารมลพิษของการเผาไหม้ธูป และยากันยุง มีค่าใกล้เคียงกัน แต่สูงกว่าค่าจากการเผาไหม้เทียนไข สาเหตุอาจเนื่องจากการเผาไหม้ธูปและยากันยุงมีจุดประสงค์ให้เกิดการเผาไหม้แบบไม่สมบูรณ์เพื่อให้เกิดควัน จากการประเมินผลกระทบต่อสุขภาพของผู้อาศัยต่อการได้รับสารมลพิษจากการเผาไหม้ธูป เทียน และยากันยุง พบว่า การเพิ่มอัตราการระบายอากาศของห้องจะสามารถช่วยลดระดับสารมลพิษในอากาศได้

คำสำคัญ: ฝุ่นขนาดเล็ก, คาร์บอนมอนอกไซด์, อัตราการปลดปล่อยสารมลพิษ, ตัวคูณการปลดปล่อยสารมลพิษ, ธูป, ยากันยุง, เทียนไข

Introduction

Poor indoor air quality has been ranked as one of the United States' greatest health risk concerns[1]. It has become a significant concern, because people spend a substantial amount of time indoors, and indoor air concentrations of pollutants can be greater than those found outdoors. Indoor pollutant emissions originate from not only building materials or furnishing, but also common household activities such as cooking, smoking, and burning of incense and candles.

Unlike western incense and candles, which are commonly used for an aesthetic purpose, burning incense and candles is prevalent in many Asian countries as a common practice for religious and spiritual purposes. In Thailand, incense sticks and candles are burned daily in spiritual rooms, houses, and temples. Incense is commonly composed of charcoal or wood powder as the combustible base, which permits self-sustained burning. Fragrant materials from either botanical sources or synthetic chemicals are also included. Candles are generally made of paraffin, which is a byproduct of petroleum refining. The candles are typically produced in various shapes, sizes, colors and scents. Candles used for religious practice in Thailand are unscented and either yellow or white in color.

Mosquito coils are also widely used as a mosquito repellent in various Asian countries including China, India, Malaysia, Korea, Japan, and Thailand. The major active components in mosquito coils are pyrethroids such as d-allethrin, esbiothrin, transfluthrin, and metofluthrin. When a mosquito coil is burned, these repellents evaporate with smoke. Mosquito coils also contain biomass, binders, dyes, and additives capable of smoldering(2). Most of the biomass used as base materials is sawdust or coconut shells/husks.

The burning of incense, candles, and mosquito coils is generally an incomplete combustion process. It is well-known that it produces various kinds of air pollutants, including particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NOx), volatile organic compounds (VOCs), and toxic metals. These pollutants may cause adverse health effects(3-4). A work indicated that burning one mosquito coil would produce the same amount of $PM_{2.5}$ mass as burning 75-137 cigarettes(2). A Hong Kong research team also studied the characteristics of the emissions of air pollutants from burning incense, mosquito coils, and candles(5-6). The average PM_{10} concentrations of all tested mosquito coils in a large environmental chamber exceeded the Good Class of Indoor Air Quality Objectives for Office Buildings and Public Places (IAQO) level of 0.18 mg/m^3. An increase of airborne mass of $PM_{2.5}$ was correlated with mortality and adverse health effects. These effects include increased respiratory symptoms, decreased lung function, increased lung cancer incidence, cardiovascular mortality, and accelerated atherosclerosis and vascular inflammation.

Despite the widely prevalent use of incense, candles, and mosquito coils in Thailand, there is a lack of data concerning their air pollutant emissions and emission factors from burning. These informative data are essential for predicting pollutant concentrations in households or temples and for assessment of occupant health risks. Thus, the objective of this study was to characterize $PM_{2.5}$ and CO emissions, which are the main pollutants from the combustion of incense, mosquito coils, and candles. All test product brands are popularly used in Thailand.

Materials and Methods

Experimental apparatus

Three brands of incense, mosquito coil, and candle, which were purchased from grocery stores in Mahasarakham province, Thailand, were tested in this study. The selected incense was a cored stick type, which had a supporting core of bamboo. The combustible base material was made from sawdust. The appearance of the selected candles was cylindrical shape with a color of either orange or yellow. They were unscented and were made of paraffin. The selected mosquito coils had an active ingredient of pyrethroids. The base material was mainly sawdust and coconut shell powder. All test emitters were cut in predetermined lengths to achieve the burning time of approximately 40 min. A single predetermined length of each test emitter was burned individually in a small experimental chamber except for the candle test of which four candles of each brand were burned at a time.

All experimental runs were conducted in an aluminum foil lined chamber with the dimensions of 1x1x1 m^3 as shown in Figure 1. A small fan with medium rotating speed was placed inside the chamber to achieve a well-mixed core. An air blower was installed on the wall to provide the chamber ventilation. The test chamber was installed in a highly ventilated room to ensure insignificant concentrations of the chamber infiltration. During each experimental run, a lit emitter tested on a small ceramic bowl was placed in the middle of the chamber. Prior to and after each run, the ceramic bowl was weighed to determine the amount of the test emitter that was burned off. Burning time was also recorded, starting from ignition until extinguishing the test emitter. Prior to the experiments, the background concentrations of $PM_{2.5}$ and CO were measured with less than 0.05 mg/m^3 and 1 ppm, respectively.

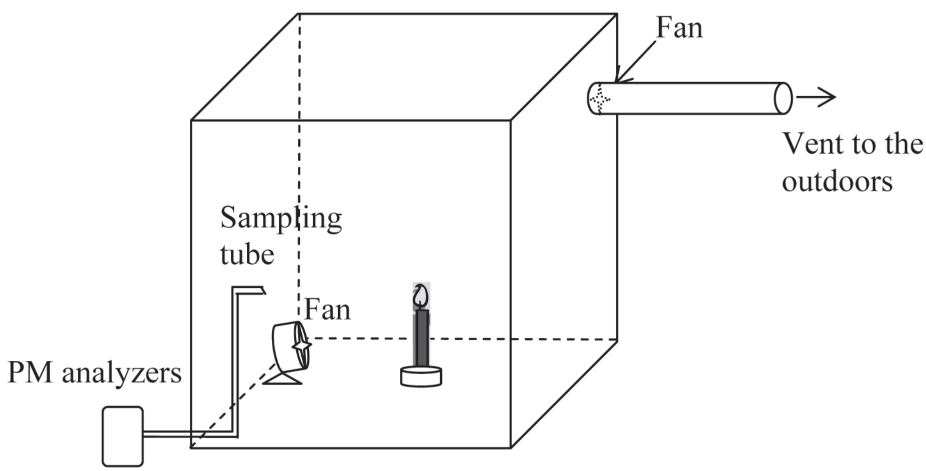

Figure 1 A schematic of experimental system.

PM and CO measurements

$PM_{2.5}$ concentration was measured with a Dusk Trak II® monitor (model 8530, TSI Inc., USA). A sampling tube was inserted in the chamber with an air sampling flow rate of 3 L/min. The detection limit of the $PM_{2.5}$ monitor was 0.001 mg/m^3. CO concentrations were measured with a Testo® 454 equipped with an ambient CO probe (Testo AG Inc., Germany). The detection range is 0-500 ppm with a resolution of 1 ppm. All data were collected and recorded every 30 s.

Modeling

The PM and CO emission rates for the test emitters were determined using a single-compartment mass balance model. The mass balance of the determined pollutant in the bulk gas phase in the well-mixed chamber during an emission period can be written as the following equation:

$$\frac{dC}{dt} = \lambda C_{out} - \lambda C - \upsilon C + \frac{E}{V} \quad (1)$$

where C is the pollutant concentration in the chamber (mg/m^3); C_{out} is the pollutant concentration outside the chamber; E is the emission rate (mg/h); V is the chamber volume (m^3); λ is the air exchange rate (/h); and ν is the indoor decay rate constant of the pollutant (/h). Assuming that the background concentrations inside and outside the chamber were all zero, and the λ and ν can be combined into the overall pollutant removal rate constant (K), the time-dependent concentration of the pollutant can be described as the following equation:

$$C = \frac{E}{VK}(1 - e^{-Kt}) \quad (2)$$

A nonlinear regression program, NLREG® version 6.3 (Advanced) (Phillip H. Sherwood, USA) was adopted to determined the parameters E and K by fitting the experimental data to equation 2. The emission factor, EF (mg/g, or milligram of pollutant emitted per gram of emitter burned), was determined by dividing the emission rate (mg/h) by the burning rate (g/h). The burning rate (BR) was obtained from the amount of emitter burned and the burning duration.

Result and Discussion

Model validation

Figure 2 shows a comparison of measured and modeled concentrations of $PM_{2.5}$ and CO for burning of incense stick, mosquito coil, and candle in the experimental chamber. Note that one of each sample brand is presented here.

As seen in Figure 2, the measured concentration profiles were in good agreement with the model fit with the value of R^2, or proportion of variance explained, varying from 0.9140 to 0.9981.

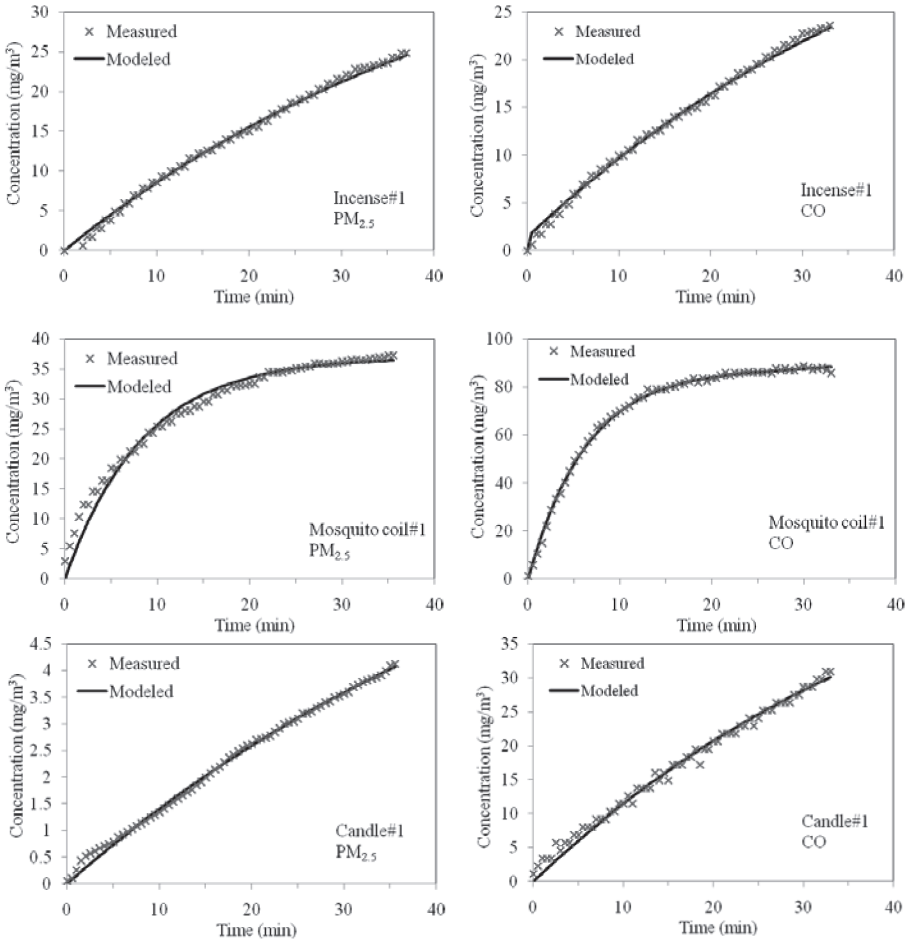

Figure 2 Comparison of measured and modeled concentration profiles for incense#1, mosquito coil#1, candle#1.

Emission rates and emission factors

Tables 1 and 2 show the values of E, K, R^2, BR, and EF for $PM_{2.5}$ and CO from burning incense sticks, mosquito coils, and candles in the test chamber, respectively. The estimates of E and K were obtained by fitting the measured time-dependent concentrations to the mass balance model using a least-squared method. Uncertainty ranges of the E and K values were based on 95% confidence intervals. The $PM_{2.5}$ emission rates and emission factors varied significantly among the test emitters, ranging from 8.81 to 1611 mg/h and from 1.87 to 252 mg/g, respectively. The $PM_{2.5}$ emission rates of the incense sticks and mosquito coils were markedly higher than those of the candles. These submicron particles are generated via the incomplete combustion of the biomass that is the base materials of the incense and mosquito coil. One of the test mosquito coils (Mosquito coil #2) emitted a very large amount of $PM_{2.5}$ up to 1611 mg/h, which is approximately five times higher than those of the two other test mosquito coils. However, the $PM_{2.5}$ emission factors for all test mosquito coils were of similar magnitude since Mosquito coil #2 burned four times faster. Different contents of base materials may contribute to the difference in emission rates and burning rates[2]. Among these test emitters, burning candles produced $PM_{2.5}$ approximately 70-75 times less than burning the same amount of either incense or mosquito coil. The significantly low emission factors of the candles are due to their low average emission rates of 9.33 mg/h, but fast burning rates.

Table 1 The values of E, K, R^2, BR, and EF for $PM_{2.5}$

Test emitter	E (mg/h)	K (/h)	R^2	BR (g/h)	EF (mg/g)
Incense #1	255±10.6	6.40±0.34	0.9835	1.01	252
Incense #2	154±1.66	3.90±0.05	0.9643	2.34	65.6
Incense #3	181±2.69	3.88±0.09	0.9981	1.74	104
Mosquito coil #1	266±16.1	7.22±0.55	0.9598	2.39	112
Mosquito coil #2	1611±68.7	12.0±0.73	0.9933	8.77	184
Mosquito coil #3	321±32.0	12.5±1.51	0.9348	1.98	162
Candle #1	9.23±0.56	1.04±0.46	0.9887	4.46	2.07
Candle #2	8.81±0.29	0.90±0.07	0.9140	4.06	2.17
Candle #3	9.97±0.56	1.23±0.39	0.9884	5.33	1.87

Table 2 The values of E, K, R^2, BR, and EF for CO

Test emitter	E (mg/h)	K (/h)	R^2	BR (g/h)	EF (mg/g)
Incense #1	378±11.8	5.33±0.26	0.9935	1.01	373
Incense #2	567±18.2	7.23±0.28	0.9870	2.34	242
Incense #3	790±47.1	12.9±0.80	0.9727	1.74	454
Mosquito coil #1	837±15.8	9.52±0.24	0.9980	2.39	350
Mosquito coil #2	722±41.5	9.30±0.77	0.9156	8.77	82.4
Mosquito coil #3	731±39.0	11.4±0.75	0.9846	1.98	386
Candle #1	76.8±3.22	1.33±0.22	0.9889	4.46	17.2
Candle #2	74.7±1.52	0.89±0.07	0.9542	4.06	18.4
Candle #3	75.8±2.71	1.69±0.16	0.9678	5.33	14.2

Similarly, highest CO emission rates were observed for both incense and mosquito coil combustion (Table 2). Comparison of mosquito coil and incense burning reveals the relatively close values of CO emission factors, ranging from 82.4 to 454 mg/g. Incense and mosquito coils are produced purposely to combust incompletely for a smoldering effect. This is contrast to candle burning of which only the candle wick is flamed. Thus, fewer amounts of incomplete combustion products would be generated from candle combustion as compared with the same amount of burned materials[6].

Comparison among oversea studies

Tables 3 and 4 are summaries on PM and CO emission rates and emission factors from the combustion of incense, mosquito coil, and candle tested in other countries, respectively.

Among the test mosquito coils made in different countries, the Thai test mosquito coils had significantly higher PM emission rates. However, the average emission rate of the Thai mosquito coil samples, with the exclusion of Mosquito coil #2, was anywhere from twice to nearly four times greater than those of the Malaysian coil and the coils made in China and Hong Kong, respectively. The result of CO emission comparison between Hong Kong and Thailand shows the higher emission rate and emission factor for the Thai incense. A work indicated that different contents of organic fillers used for smoldering could contribute to the difference in PM emission rates[2]. Furthermore, the relatively high ventilation rates of the test chamber used in this study may cause larger pollutant concentration gradients between the surface of the test emitter and the bulk air, which could in turn affect the pollutant emission rates. In contrast to the mosquito coil and incense results, the average PM emission rate and emission factor of the Thai test candles and US candles were similar. The test candles in this study and in the USA study were unscented and paraffin waxed. However, the CO emission rate of the Thai candles was approximately 15 times higher than that of the US candles. This high CO emission may be due to the limiting rate of oxygen transport to the candle surface, even though sufficient oxygen was provided to the chamber for combustion.

Table 3 Summary on PM emission rates and emission factors from household combustion emitters

Country[a]	Incense		Mosquito coil		Candle	
	E (mg/h)	EF (mg/g)	E (mg/h)	EF (mg/g)	E (mg/h)	EF (mg/g)
Thailand[b]	197[c]	141[c]	733[c]	152[c]	9.33[c]	2.03[c]
USA (7)	-	-	-	-	13.3[c,d]	0.87[c,d]
Malaysia (2)	-	-	116[c]	69.5[c]	-	-
China (2)	-	-	67.5[c]	39.8[c]	-	-
Hong Kong (6)	-	-	72.4[c]	32.5[c]	-	-

[a] Country from where the test emitter was purchased[b] Current study[c] Average values[d] PM_{10}

Table 4 Summary on CO emission rates and emission factors from household combustion emitters

Country[a]	Incense		Mosquito coil		Candle	
	E (mg/h)	EF (mg/g)	E (mg/h)	EF (mg/g)	E (mg/h)	EF (mg/g)
Thailand[b]	578[c]	356[c]	763[c]	267[c]	75.8[c]	16.6[c]
USA (6)	-	-	-	-	4.7[c]	0.31[c,d]
Hong Kong (5)	183[c]	82.4[c]	-	-	-	-

[a] Country from where the test emitter was purchased[b] Current study[c] Average values

Implications for exposure

The impacts of burning of the combustible household products on occupant exposure to $PM_{2.5}$ and CO under a realistic situation were investigated. In this simulation, the single compartment mass balance model of the targeted air pollutants and parameter values of emission rates obtained from this study were used to predict time-dependent pollutant concentrations in a typical room such as a tabernacle in which three incense sticks and one candle are burned. Simulation conditions are given as follows: the room volume of 22.5 m^3, the total surface area of 48 m^2, the indoor decay rate constants of 0.2 /h for $PM_{2.5}$ (8) and 0 /h for CO (relatively inert gas), the average $PM_{2.5}$ emission rates of 197 mg/h/ an incense stick and 9.33 mg/h/ a candle, the average CO emission rates of 578 mg/h/ an incense stick and 75.8 mg/h/ a candle. The simulation assumes that indoor air mixes rapidly and thoroughly in a room. Figures 3 (a) and 3 (b) show the predicted time-dependent concentrations of $PM_{2.5}$ and CO in a room with four different air exchange rates, i.e., 0.5, 1, 2, and 4/h, when burning three incense sticks and one candle.

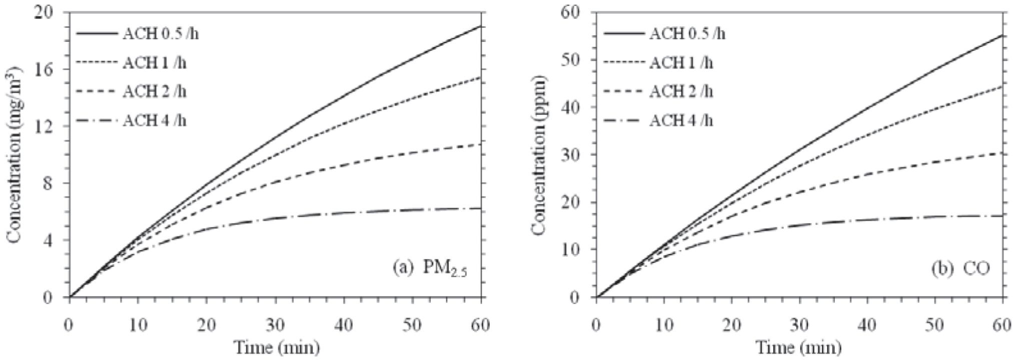

Figure 3 Predicted time-dependent concentrations when burning three incense sticks and one candle in a room with four different air exchange rates for (a) $PM_{2.5}$ and (b) CO.

It is evident that the room air exchange rate strongly influences the dynamic concentrations of $PM_{2.5}$ and CO in room air. The $PM_{2.5}$ and CO concentrations in the simulated air-tight room with a low ventilation rate of 0.5/h are predicted to be 19 mg/m^3 and 55 ppm, respectively, at the end of a 1-hour combustion period. The predicted concentration of $PM_{2.5}$ exceeds the 24-hour $PM_{2.5}$ standard of 65 μg/m^3 for the US National Ambient Air Quality Standards (NAAQSs)[9]. As a result of exposure to the average 1-hour CO concentration of 30 ppm, the level of carboxyhemoglobin (COHb) in an occupant's blood is expected to be 1.3%. This COHb level could affect on behavioral performance[9]. As the air exchange rate increases from 0.5 to 4/h, the $PM_{2.5}$ and CO concentrations decrease by 67%. The increased ventilation rate of a room is suggested to reduce health risks of customers exposed to the released air pollutants.

Conclusion

Three types of household combustion emitters were tested for their emissions of $PM_{2.5}$ and CO. The results show that the combustion of incense sticks, mosquito coils, and candles emitted $PM_{2.5}$ at the average rates of 197, 733, and 9.33 mg/h, while they emitted CO at 578, 763, and 75.8 mg/h, respectively. Comparison with the overseas studies reveals that the emission rates and emission factors of both pollutants from the products purchased in Thailand were higher than those of the products in the oversea studies, except for the $PM_{2.5}$ emission of the candles. The model simulations also indicated that burning these household products in an enclosed room is likely to produce harmful levels of the released air pollutants, thus in part resulting in adverse health effects. Increasing room ventilation rate could alleviate customer exposure to these high pollutant levels.

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