Fine Particulate Matter Emissions from Candles

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ABSTRACT

Five types of candles purchased from local stores were tested for fine particulate matter (PM) emissions under close-to-realistic conditions in a research house. The test method allows for determination of both the emission rate and deposition rate. Most tests revealed low PM emission rate except two, in which excessive sooting occurred and the PM concentration approached 1000 $\mu g/m^3$ with six and nine burning wicks, respectively. Wax breakthrough significantly increased the PM emission rate. Smoldering generated more fine PM than several hours of normal burning, causing very high concentrations in a short period of time, which raises concern over potentially acute health effects, especially for children and the elderly. A simple source model is proposed to represent both stable PM emissions during normal combustion conditions and the sudden concentration surge following flame extinction.

INTRODUCTION

Candles have been associated with human living conditions for at least 1000 years. Although no longer a major means of lighting in modern society, they are still widely used in homes, mostly for creating unique, warm, and tranquil atmospheres. It was believed from observation that the candle flame produces carbon particles and that, under perfect combustion conditions, the carbon is totally consumed by the flame. In his famous book *The Chemical History of a Candle*, originally published in 1861,[1] Michael Faraday -- one of the greatest experimental scientists of

all time -- uses simple, yet very ingenious, experimental methods to prove that carbon particles exist in the candle flame and that it is these solid particles that create "the very beauty and life of the flame." He further points out that, under imperfect combustion conditions, the carbon particles cannot be consumed entirely by the flame, resulting in emissions of soot.

In recent years, concerns over the impact of candle burning, especially the property damage they may cause due to soot deposition, have been on the rise.[2,3,4,5] Analysis of the potential impact on human health due to inhalation of particulate matter (PM) has also been reported.[5] According to the study by Fine et al.,[2] a sooting flame and a smoldering wick produce much higher fine particle mass emission rates than a quiet normal burning candle and are responsible for the vast majority of fine particle emissions from this source. Another human-health-related issue associated with candle burning is the inhalation of particleborne lead (Pb) generated by certain types of candles, whose wicks have a lead core.[6,7]

This paper investigates the PM emissions from candles under close-to-realistic conditions and their contribution to indoor PM levels with emphasis on the fine fraction of the PM -- particles having aerodynamic diameters of less than 2.5 μm ($PM_{2.5}$). The goals were to: identify the emission patterns, measure the emissions under certain real-life scenarios, and determine the key parameters needed for estimating inhalation exposure.

EXPERIMENTAL

Test Facility

Emissions tests were performed in a research house located in Cary, NC.[8] One bedroom, used as a test chamber, was isolated from the rest of the house by blocking the air supply registers and closing the interior door. The room has dimensions of 3.78 (length) × 3.28 (width) × 2.44

(height) m. It has vinyl flooring, painted gypsum board walls, and a textured gypsum board ceiling. The particle-free air supply was generated by an in-line fan (FanTeck Model FR250, 230 W), which passed outdoor air through a high efficiency particle air (HEPA) filter into the test room, keeping the room under slightly positive pressure (~2 Pa) to prevent the infiltration of particles from the outdoors and adjacent rooms. Prior to a test, a stand-alone HEPA filter air cleaner (Bionaire, Model CH-3580 or Honeywell Enviracaire, Model 13520) operated inside the test room for 30 minutes to reduce the background fine PM concentration to less than 2 $\mu g/m^3$. A ceiling fan was used to keep the room air well mixed. The test candles were placed on a table away from the direct air draft created by the ceiling fan. Under the standard test conditions, the ceiling fan was set at low speed and normal wind direction (i.e., downward), which gave an average air speed of 11 cm/s near the top of the candle -- close to the air speed commonly found in indoor environments. Other speed/direction combinations of the ceiling fan provided an air speed range from 14 to 27 cm/s near the candle. When the fan was turned off, the air speed was reduced to less than 5 cm/s. Additional discussions of this test facility can be found in these proceedings.[9]

Test Specimens

All candles tested were purchased from local stores and are described in Table 1.

Table 1. Description of test candles [a]

Sample ID	Type	Shape of Cross Section	No. of Wicks	Color
P1	paraffin/aroma	square	9	orange
P2	paraffin/aroma	square	9	red
P3	paraffin/aroma	round	3	mauve
BW1	beeswax	round	1	yellow
BD1	birthday candle [b]	round	1	white

[a] P1 and P2 are made by the same manufacturer.
[b] Material type was not mentioned on the label.

PM Sampling

Particles with aerodynamic diameters of less than 10 μm (PM_{10}) and less than 2.5 μm were sampled simultaneously onto Teflon filters, using cyclones (University Research Glass) with corresponding size cut-points. Each cyclone has a two-stage filter pack (47-mm, R2PJ047). The mass concentrations of $PM_{2.5}$ and PM_{10} were determined gravimetrically. The PM size distribution and real-time concentration were determined with an electric low pressure impactor, or ELPI (Dekati Ltd.)[10], which measures an aerodynamic diameter range from 0.03 to 10 μm with 12 stages, and has a response time of 5 sec while experiment data were recorded every 60 sec.

Test Method

The ELPI was used to monitor the indoor PM concentrations throughout the experiment. After the room was pressurized and the background PM concentration reduced to less than 2 $\mu g/m^3$, the test candle was lit with a butane lighter. Matches were used to light the birthday candles. The

burning duration was 8 minutes for the birthday candles and 4 to 6 hours for the other candles. In the latter case, the candles were allowed to burn for 1 hour before filter sampling. After the test candles were extinguished, the EPLI continued to operate for at least 4 more hours. Sulfur hexafluoride (SF_6) tracer gas was injected after the extinction of the flame to determine the ventilation rate and the PM deposition rate. No SF_6 was injected prior to or during the burning period because of possible decomposition of SF_6 when in contact with a flame, resulting in interferences.[11]

RESULTS

Correlation Between the Gravimetric Method and ELPI

Comparison of paired fine PM concentration data showed that, in the low concentration range (< 5 μg/m³), the two methods agree with each other reasonably well and that the ELPI gave higher readings as the concentration increased (Figure 1). A good correlation exists between the two methods, however. In this paper, all the ELPI data were corrected based on Equation 1:

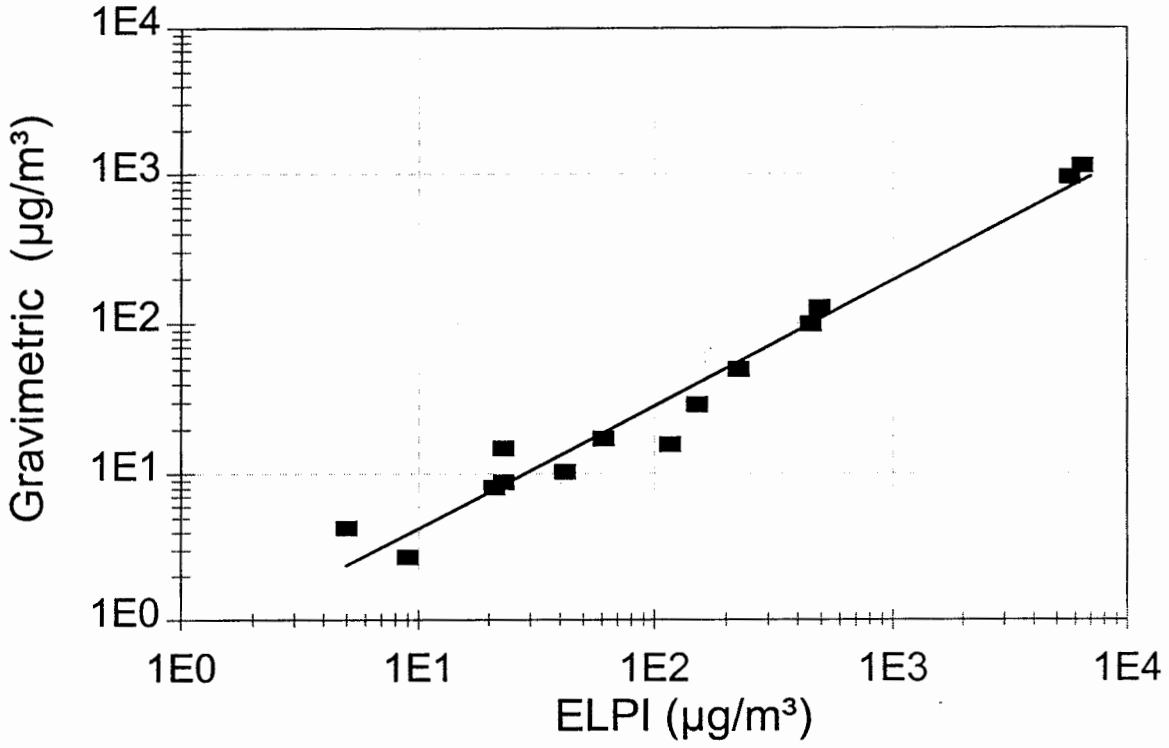
Equation 1. Correlation between the gravimetric method and ELPI for fine PM concentrations

$$\ln C_{grav} = 0.829 \ln C_{ELPI} - 0.475 \qquad (r^2 = 0.967, n = 14)$$

where C_{grav} = fine PM concentration from the gravimetric method (μg/m³), and

C_{ELPI} = fine PM concentration from the ELPI (μg/m³).

Figure 1. Correlation between the gravimetric method and ELPI for fine PM



PM Concentrations and Emission Rates by the Gravimetric Method

The average concentration and emission rate calculated from the filter samples are presented in Table 2. In most cases, the fine PM concentration was low except in two tests for candle P2, in which excessive sooting occurred and the fine PM concentration reached 955 and 1137 µg/m³, respectively. These unusually high concentration results were supported by the ELPI data. A higher burn rate in test C121499 is another indication of possible imperfect combustion. However, no visual observations were made during these tests and we were unable to determine the exact causes of the high emission rates.

Table 2. Average fine PM concentrations and emission rates based on filter samples

Test Candle	Test ID	Wicks Lighted	Burn Rate (g/h/wick)	Air Speed (cm/s)	ACH (h^{-1})	Concentration ($\mu g/m^3$)	Emission Rate ($\mu g/h/wick$)
P1	C121399	9	2.77	11	0.99	99.6	329
P2	C121699	9	3.71	< 5	0.95	13.0 [a]	41
	C121499	9	4.67	11	0.98	955	3120
	C121599	6	NA [b]	11	0.93	1137	5287
	C121799	1	2.29	14	1.1	15.8	521
	C041100	1	3.33	15	1.56	8.79	411
	C041200	1	2.50	27	1.51	8.13	368
P3	C051600	9 [c]	3.89	11	1.54	14.9	76
	C051700	9 [c]	4.00	11	1.5	17.3	87
BW1	C041700	1	7.86	14	1.45	4.32	188

[a] This value is based on the ELPI data. The result from filter samples was discarded because the relative standard deviation for duplicate samples was too large.
[b] Burn rate was not measured in this test.
[c] Three 3-wick candles.

PM Size Distribution

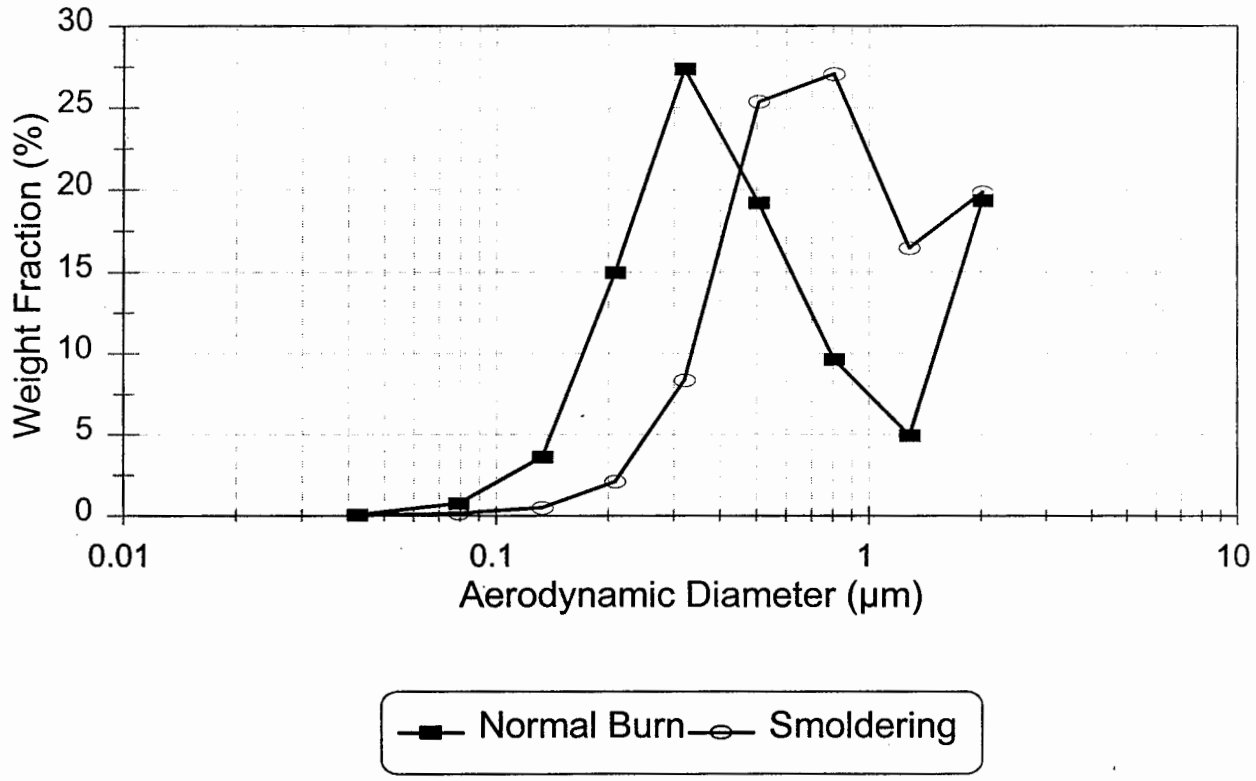
Most particles emitted from candles were in the fine particle size range. This is evidenced by the fact that the filter samples for $PM_{2.5}$ and PM_{10} taken in parallel are almost the same in most tests (Table 3). Typical size distribution for fine PM is shown in Figure 2. Like some other combustion sources, two peaks appear in the size distribution. Although smoldering creates more larger particles, the shape of the distribution curve did not change significantly.

Table 3. Comparison of filter samples for $PM_{2.5}$ and PM_{10}

Concentration (μg/m³) [a]		Percent Difference [b]
$PM_{2.5}$	PM_{10}	
2.7 ± 0.5	3.4 ± 0.2	23.7
8.1 [c]	8.6 [c]	5.5
10.3 ± 0.4	11.3 ± 0.9	9.8
14.9 ± 4.6	15.2 ± 5.1	1.9
15.8 ± 3.0	16.7 ± 1.5	5.1
17.3 ± 1.1	18.5 ± 1.4	7.1
29.2 ± 2.5	29.1 ± 0.1	-0.5
49.8 ± 1.7	50.8 [c]	2.0
99.6 ± 2.5	99.6 ± 2.5	0.0
955 ± 3.2	951 ± 20.2	-0.5
1137 ± 248	1128 ± 86.7	-0.8

[a] Mean ± standard deviation for duplicate samples.
[b] Percent = $2 \times (PM_{10} - PM_{2.5}) / (PM_{10} + PM_{2.5}) \times 100$.
[c] Single filter sample.

Figure 2. Fine PM size distribution observed in test C051600



Emission Patterns

General Emission Patterns

The real-time concentration data from the ELPI were used to determine the PM emission patterns. In most cases, the fine PM emission rate was fairly steady during the normal burning period. However, the emission rate was higher immediately after the candle was lit. Two slightly different emission patterns are shown in Figures 3 and 4. In both cases, a concentration surge occurred when the flame was extinguished. In most tests, the smoldering period generated more particles in a few seconds than during the whole period of normal burning. Emissions due to smoldering are discussed further in the following section. Also note that the emissions data from filter samples presented in Table 2 do not include the smoldering period because the sampling pumps were turned off before the candles were extinguished.

Figure 3. Fine PM concentration profiles for candle P3 in duplicate tests

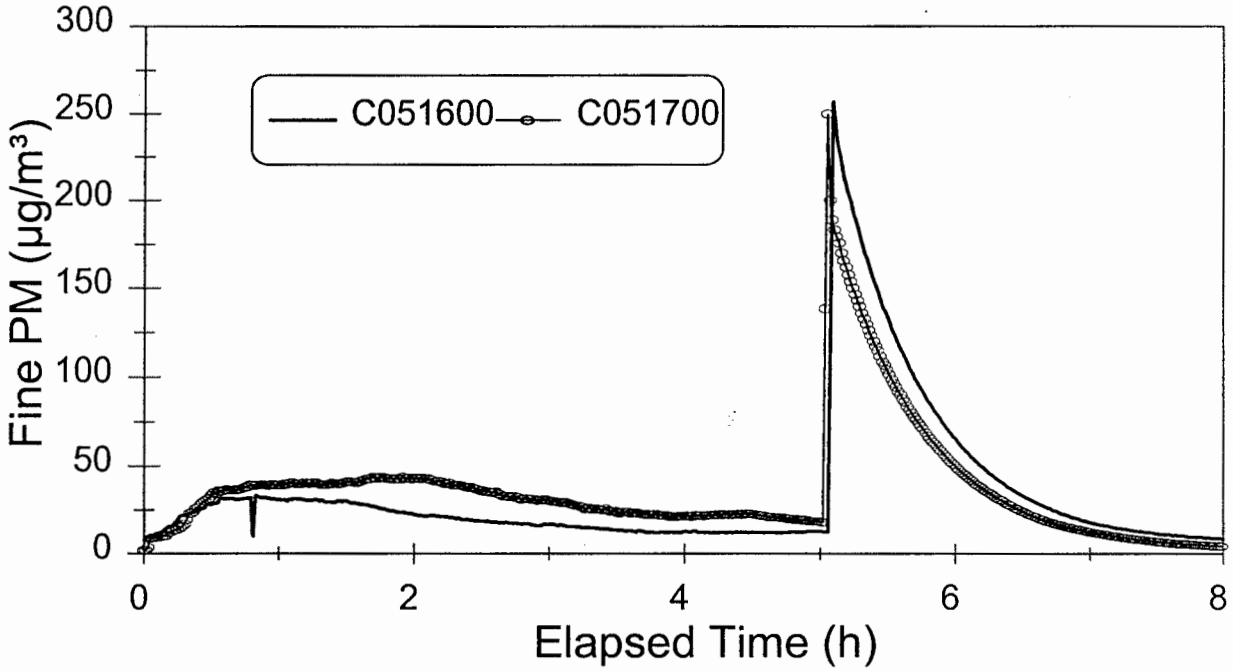
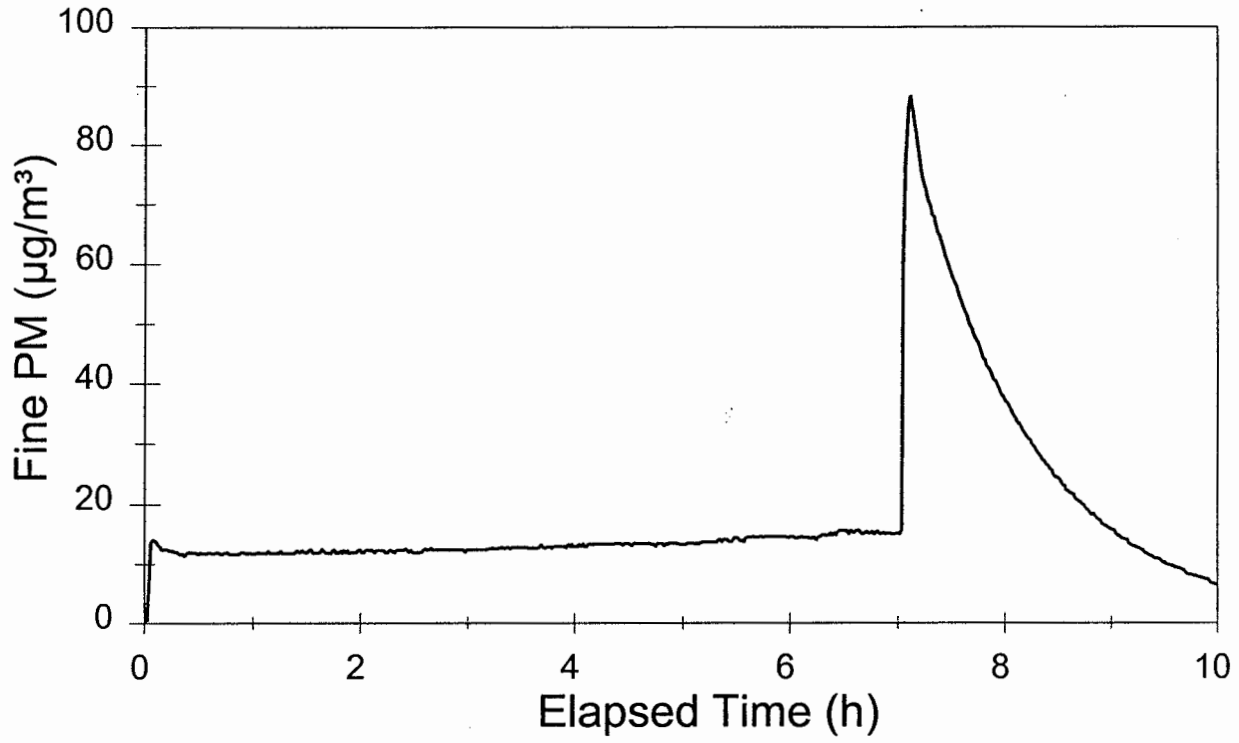


Figure 4. Fine PM concentration profile for candle P2 in test C121699



Given the very high concentrations that occurred during the smoldering period, certain acute health effects may be of concern. While exposure estimation based on time-averaged emission rates may be adequate for chronic effects,[5] time-varying emission rates may be necessary for study of acute effects.

Estimation of Fine PM Emissions During Smoldering

The amount of $PM_{2.5}$ released during the smoldering period was calculated from the following mass balance equation.

Equation 2. Calculation of the amount of PM mass emitted during the smoldering period

$$W_x = Q \int_{t_x}^{t_n} C(t)\,dt - V\,C(t_x) + V\,C(t_n)$$

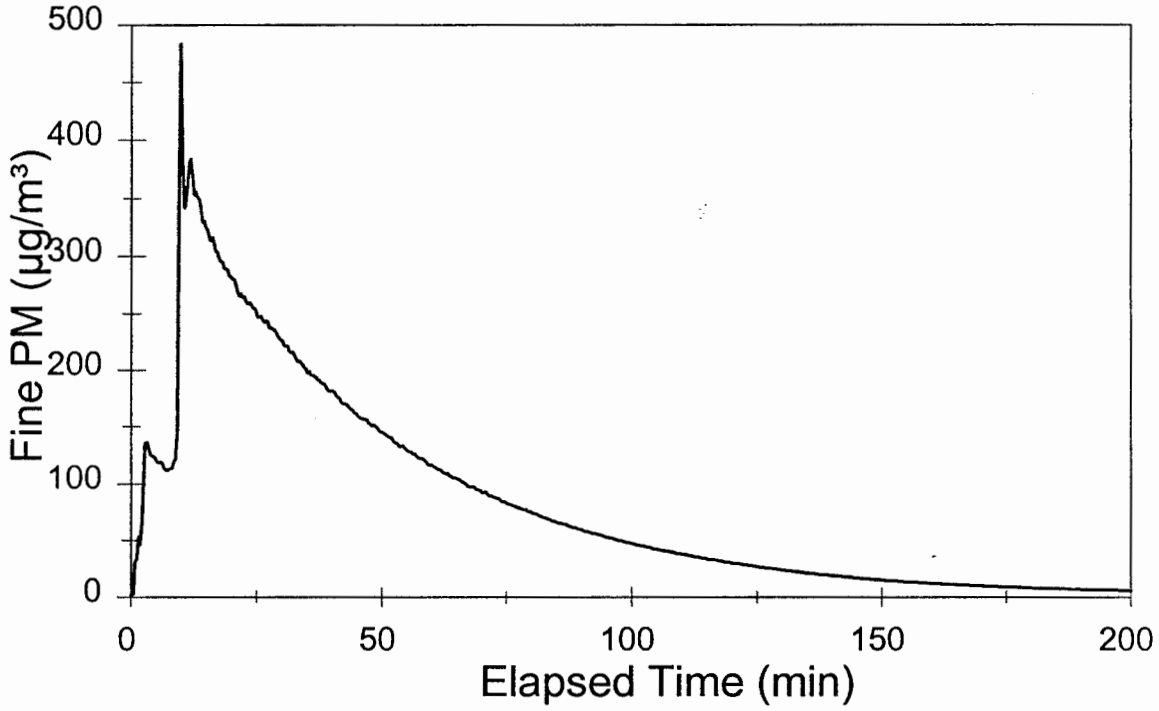
where W_x = amount of fine PM emitted during smoldering period (μg), Q = ventilation flow rate (m^3/h), C = fine PM concentration ($\mu g/m^3$), t = time (h), V = room volume (m^3), t_x = time at which the flame is extinguished (h), and t_n = time for the last data point (h).

The time-concentration curve was integrated using the trapezoidal rule, and the calculated emissions from smoldering are presented in Table 4. It appears that candle P3 emits more fine PM during the smoldering period than the other two paraffin candles, although it emits less during the normal burning period (see Table 2). Results in Table 4 also suggest that using a snuffer to extinguish the flame produced less PM than blowing out the flame. Blowing out 30 birthday candles produced the highest fine PM concentration in the room (about 500 $\mu g/m^3$ in the mixed air), and the concentration remained above 100 $\mu g/m^3$ for more than an hour (Figure 5).

Table 4. Amounts of fine PM emitted due to smoldering

Test ID	Candle	Number of wicks	Extinguishing Method	Peak Conc. ($\mu g/m^3$)	Emissions (μg/wick)
C121399	P1	9	blowout	144	273
C121699	P2	9	blowout	88.3	261
C051900	P3	9	blowout	153	262
C051600		9	blowout	257	609
C051700		9	blowout	250	650
C052300		9	blowout	213	554
C051900		9	snuffer	82	115
C041700	BW1	1	blowout	32.5	816
C050800	BD1	30	blowout	483	151

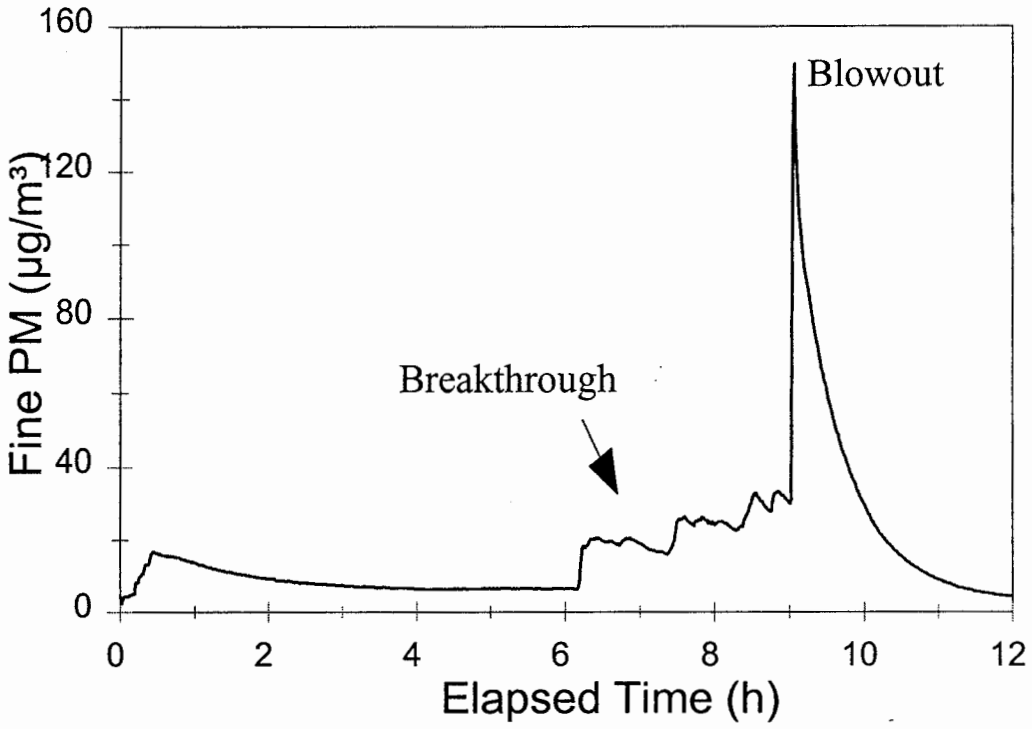
Figure 5. Fine PM concentration profile for lighting and blowing out 30 birthday candles



Emissions after Wax Breakthrough

Wax breakthrough occurs when the rim of the solid wax surrounding the liquid pool softens from the heat of the flame and slumps off to one side of the candles, causing the release of the liquid wax from the pool that has concentrated around the wick. It is one way to cause imperfect combustion. Wax breakthrough occurred in one test with candle P3. As shown in Figure 6, a higher emission rate resulted.

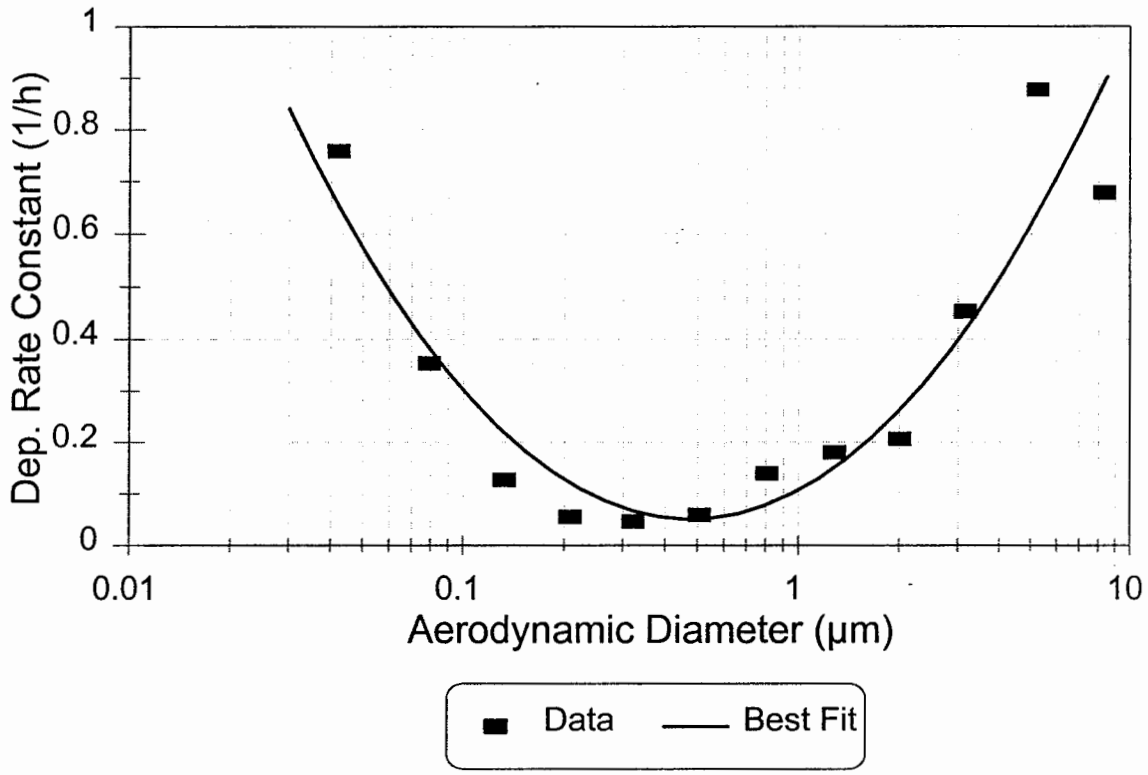
Figure 6. Effect of wax breakthrough on fine PM emissions (test C051800)



PM Deposition Rates

PM deposition rate is an important parameter to estimate the PM concentrations from indoor air quality simulation. In this work, the decay part of the ELPI data (i.e., after the candle was extinguished) was used to estimate this parameter. The first-order deposition rate constant was calculated by comparing the decay rate for PM with that for the tracer gas. As shown in Figure 7, a U-shaped curve was obtained. Note that the emission rate data presented in Table 2 do not consider PM deposition and thus should be considered as the lower bound of the actual emission rate.[9]

Figure 7. First-order deposition rate constants for test C121699



MODELING CONSIDERATIONS

Source Model

Considering the unique emission pattern for PM emissions from candles, an average emissions rate may not be adequate for exposure estimation, especially when acute health effects are of concern. A simple model, represented by Equations 3 and 4, is proposed to account for emissions for both normal burning and smoldering:

Equations 3 and 4. Model for PM emissions from candle burning

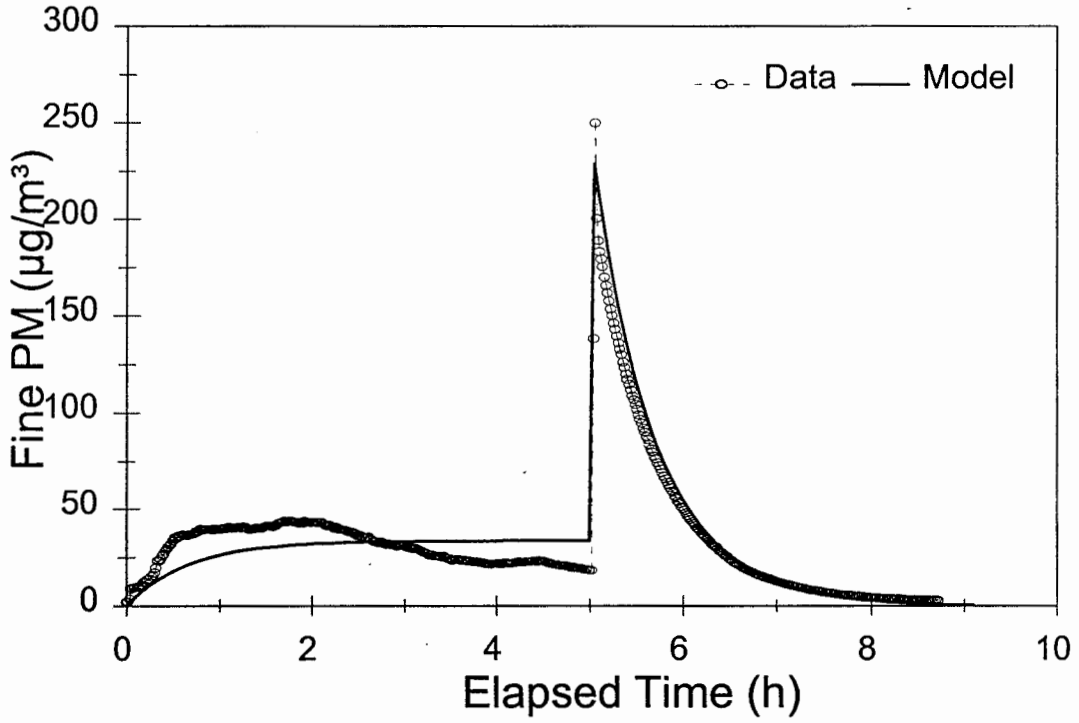
$$R = R_n \qquad \text{for } t_0 < t < t_x$$

$$\Delta C = \frac{W_x}{V} \qquad \text{at } t = t_x$$

where R = PM emission rate (μg/h), R_n = constant emission rate during the normal combustion period from t_0 (burning start time) to t_x (μg/h), and ΔC = an instant increase of PM concentration in room air at t_x (μg/m³).

This model can be easily implemented in a spreadsheet or an indoor air quality simulation program. An example application of this model is shown in Figure 8.

Figure 8. Modeling of test C051700 using Equations 3 and 4 as a source model



PM Accumulation on Interior Surfaces

With knowledge of both the emission rate and deposition rate, the amount of PM deposited on interior surfaces can be estimated from Equations 5 and 6. An example simulation shown in Figure 9 represents a simple case, in which all interior surfaces are treated as the same type and an average deposition rate constant of 0.4 h^{-1}, which is equivalent to a deposition velocity of 0.2 m/h in the test room, was used for fine PM.

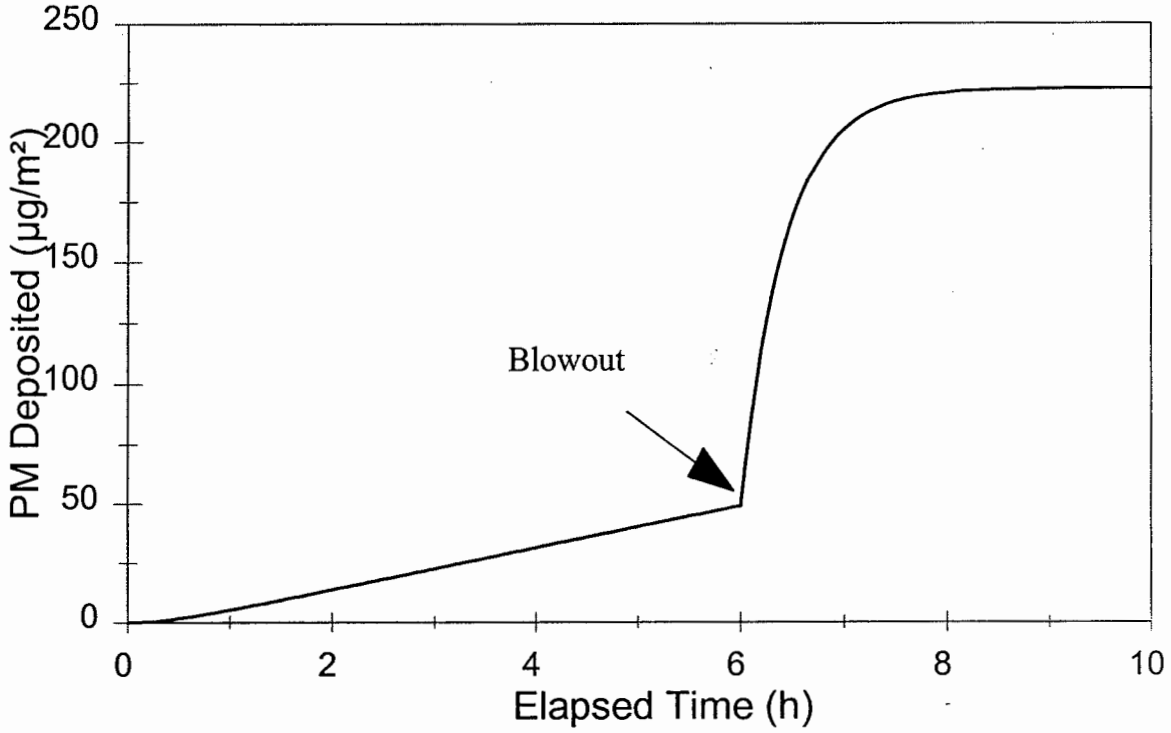
Equations 5 and 6. Estimation of PM deposition on interior surfaces

$$V\frac{dC}{dt} = R - QC - C\sum_{i=1}^{n}(S_i D_i)$$

$$\frac{dM_i}{dt} = D_i C$$

where n = number of interior surface types, S_i = area of surface i (m^2), D_i = PM deposition velocity for surface i (m/h), and M_i = amount of PM accumulated on surface i ($\mu g/m^2$).

Figure 9. An example simulation of PM accumulation on interior surfaces in the test room



CONCLUSION

Under normal combustion conditions, the candles tested do not produce significant amounts of particles -- the average $PM_{2.5}$ emission rate ranges from 41 to 521 µg/h/wick. Excessive sooting occurred in two tests with average $PM_{2.5}$ concentration approaching 1000 µg/m³ and an emission rate in the 3000 to 5000 µg/h/wick range. However, the exact cause of sooting is not clear. Smoldering often generates more particles than several hours of normal burning. The amount of $PM_{2.5}$ emitted from extinguishing the flame ranges from 115 to 569 µg/wick. In a similar test

with 30 birthday candles, the peak fine PM concentration was near 500 $\mu g/m^3$ after extinguishing the flames. Given the dramatic concentration surge due to smoldering, using an average emission rate to represent the fine PM emissions from candles may not be adequate for exposure estimation in some cases, especially when acute health effects are of concern. As a first approximation, a combination of constant and instant source models is recommended.

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