Sidestream cigarette smoke: a low cost monitoring system to evaluate PM_{10} and $PM_{2.5}$ emission factors

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Abstract

Cigarette smoke contains several toxic compounds that have harmful health effects on exposed individuals. This study determines the emission factors of particulate matter in sidestream cigarette smoke. The scope of this study included monitoring of PM_{10} and $PM_{2.5}$ concentrations in sidestream smoke in a test chamber for various cigarette-burning scenarios using a continuous monitor, DataRAM. This instrument is based on the nephelometric principle to sense the light scattered by particles which is then translated into mass concentrations. The peak concentrations observed; the volume of the test chamber, the number of cigarettes burnt, and the weight of the tobacco burnt were used in calculating the emission factors, and are expressed as "µg/cigarette" and "µg/mg of tobacco burnt." Statistical analysis was performed to observe the relationship between the $PM_{10}/PM_{2.5}$ concentrations and the number of cigarettes burnt in the test chamber. The linear relationship observed between concentrations and the number of cigarettes with an r^2 value of 0.93 for PM_{10} and 0.97 for $PM_{2.5}$ indicates an excellent correlation between the parameters studied. The F-test results and the confidence levels indicate the significance of the relationship between the concentrations observed and the number of cigarettes, along with the appropriateness of the test method adopted in this research. The results of this research are useful in risk assessment studies for different scenarios.

Keywords: cigarette smoking, sidestream smoke, PM_{10}, $PM_{2.5}$, emission factors.

1 Introduction

Evidence that passive smoking causes respiratory illnesses in humans emerged during the 1970s and studies demonstrating health effects in adult non-smokers began to be reported in the early 1980s. The Canadian Cancer Society has defined mainstream smoke as the smoke inhaled first by the smoker and then exhaled. Sidestream smoke has been defined as the smoke that goes directly into the air from the end of a burning cigarette. Mainstream and sidestream smoke (components of secondhand smoke) both contain a large number of chemical carcinogens and toxic substances. Sidestream smoke contains greater amounts of toxic chemicals (NH_3, C_6H_6, CO, nicotine, 2-Naphthylamine, 4-Aminobiphenyl, N-nitrosamines, benz[a]anthracene, and benzo-pyrene) per mg of tobacco burnt. The particles in sidestream smoke are smaller than those in mainstream smoke, meaning that they can be inhaled more deeply into the lungs [1].

It has been estimated that 80% of the smoke present in an average room in which smoking has occurred is composed of sidestream smoke. Passive smokers have a lower exposure to the harmful components of tobacco smoke than active smokers. Sidestream smoke inhalation by non-smokers depends on the filtration, tar level and quantity of cigarettes smoked, room size, ventilation rates, and duration of exposure. Passive smoking can lead to serious health effects such as: increased bronchitis, pneumonia and other chest illnesses in children, lung cancer and other lung disease, cardiovascular diseases, "irritant" effects to the eyes, nose, throat, and airway passages [1]. Surprisingly very little has been done on the quantification of emissions. Limited studies have been conducted to quantify the emissions of particulate matter (PM_{10} and $PM_{2.5}$) from cigarette smoke [2].

The main objective of this study was to determine emission factors for PM_{10} and $PM_{2.5}$ applicable to secondhand cigarette smoking. The specific objectives were to:

- Measure $PM_{10}/PM_{2.5}$ concentrations in an enclosed test chamber for a different number of cigarettes burnt using a continuous $PM_{10}/PM_{2.5}$ monitor,
- Determine the relationship between $PM_{10}/PM_{2.5}$ concentrations and the number of cigarettes burnt and validate the relationship using statistical techniques,
- Determine emission factors for $PM_{10}/PM_{2.5}$ (mass of pollutant emitted/cigarette burnt; mass of pollutants emitted/mg of tobacco burnt).

The emission data will be useful in other studies for an evaluation of the direct and indirect impacts of secondhand smoke on humans and also in risk assessment for different smoking scenarios.

2 Particulate matter: regulations, health effects, and relation to cigarette smoking

Inhalable particles are very small solids or liquid aerosols that vary in size and chemical composition. Those ranging in size up to 10 μm in diameter are referred to as PM_{10} whereas those particles with a diameter up to 2.5 μm are referred to as $PM_{2.5}$. PM_{10} and $PM_{2.5}$ particles can be made up of many constituents, including sulfates, nitrates, elemental carbon, organic compounds, metals, and soil dust. This variability in composition reflects the source of the material. PM_{10} particles are easily inhaled and the smaller size particles ($PM_{2.5}$) can travel to and affect the deepest part of the respiratory tract. Ambient levels of PM_{10} and $PM_{2.5}$ result from particles that are emitted directly into the atmosphere (primary particles) or from those by reactions of gaseous pollutants in the atmosphere (secondary particles) [3].

Sidestream cigarette smoke contains PM_{10} and $PM_{2.5}$, which is the focus of this study. Inhalable particulates ($PM_{10}/PM_{2.5}$) have been linked to increased mortality. Studies show that an increase of 10 $\mu g/m^3$ could increase the total mortality rate by one percent. A study on passive smoking (Department of Epidemiology in the Harvard School of Public Health) proved that current indoor exposure to $PM_{2.5}$ increases the cumulative incidence of lower respiratory symptoms, but is only weakly associated with decreased pulmonary function level in preadolescent children [4].

3 Methodology

To meet the objectives of the study, the research methodology included the following tasks:

- Identifying and installing a test chamber for the experiment;
- Measuring $PM_{10}/PM_{2.5}$ concentrations resulting from cigarette smoke by using a continuous aerosol monitor;
- Analyzing the data to establish the relationships between the concentrations measured ($PM_{10}/PM_{2.5}$ in $\mu g/m^3$), the number of cigarettes burnt, and the time; and
- Determining emission factors for PM_{10} and $PM_{2.5}$ (μg/cigarette, μg/mg of tobacco burnt) applicable to cigarette smoking.

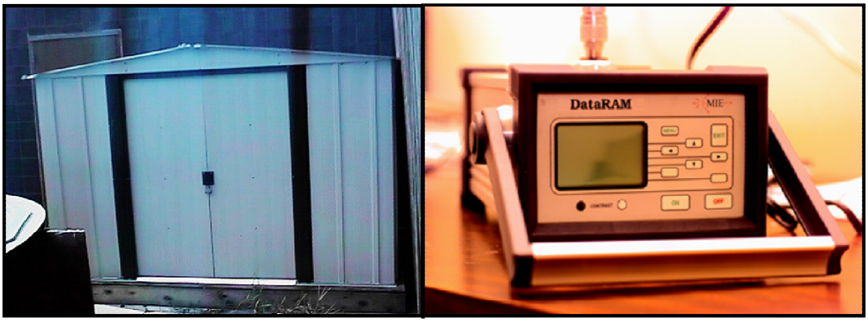

Figure 1: Test chamber (left), MIE DataRAM (right).

3.1 Test chamber and sampling equipment

A vinyl-coated storage shed was used as test chamber (94.75" X 66" X 77.86"). The MIE DataRAM Real-time Aerosol Monitor is designed to sample the air and

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to measure the concentration of airborne particles. It provides direct and continuous readout as well as electronic recording of the information [4]. Figure 1 shows the test chamber and DataRAM monitor.

3.2 Cigarettes used

The cigarette brand selected for the study was Marlboro Light, one of the most popular brands in the United States. Each Marlboro light cigarette weighs 0.9 g, and contains 13.11 mg of nicotine and 10 mg of tar.

DataRAM is a highly sensitive nephelometric monitor whose light scattering sensing configuration is optimized for the measurement of airborne dust, smoke, and fume concentrations. The measurement range of DataRAM is from 0.0001 mg/m^3 (0.1 $\mu g/m^3$) to 400 mg/m^3, a total span of 4 million times, corresponding to the most pristine ambient air levels up to extremely polluted source conditions. The information stored in the DataRAM includes time and date, average concentration over selected periods, maximum and minimum values, short-term exposure limits (STEL), as well as a tagging code [4].

3.3 Sampling procedure

DataRAM was placed inside the test chamber (volume = 7.96 m^3), and was run continuously for 5-6 hours. During this time, a small fan was used inside the test chamber to keep the particulates well distributed within the chamber. Cigarettes were burnt for nine minutes (up to the filter) at regular time intervals. The door was kept closed during the entire period the cigarettes were burnt, and also for a period of 10-15 minutes after they were extinguished to achieve enclosed conditions. Then, the enclosure was ventilated for a few minutes (usually 5 -10 minutes) until the concentration was near the background concentration (concentration inside the chamber before the cigarette was lit). This procedure was repeated to ensure reproducibility and accuracy of the results. On each sampling day, the number of cigarettes used was changed for both PM_{10} and $PM_{2.5}$ emissions. The first day, for each sampling cycle, only one cigarette was used. The next day two cigarettes were used, and so on. This was done with one, two, three, and four cigarettes burning at the same time to find the relationship between the number of cigarettes used and the PM_{10} and $PM_{2.5}$ concentrations.

4 Results and discussion

Sampling was carried out using DataRAM and PM_{10} and $PM_{2.5}$ concentrations were observed continuously for various cigarette burning scenarios. The concentrations were measured for simultaneous burning of one, two, three, and four cigarettes in the test chamber under enclosed conditions.

4.1 PM_{10} and $PM_{2.5}$ emission factors

Figure 2 shows typical graphs developed for each sampling day and variation of PM_{10} and $PM_{2.5}$ concentrations with time. Data for one, two, three, and four cigarettes burnt simultaneously were obtained and illustrations for the experiments with three and four cigarettes are presented here. The graphs shown in Figure 2 were obtained from ten experimental runs per day. A distinctive peak was observed in each graph whenever a cigarette(s) was/were burnt. This peak PM_{10}/$PM_{2.5}$ concentration and the volume of the test chamber were used in calculating the total emissions from cigarette burning. As the cigarette(s) was/were extinguished and as the enclosure was ventilated, the concentration was found to return to near background values.

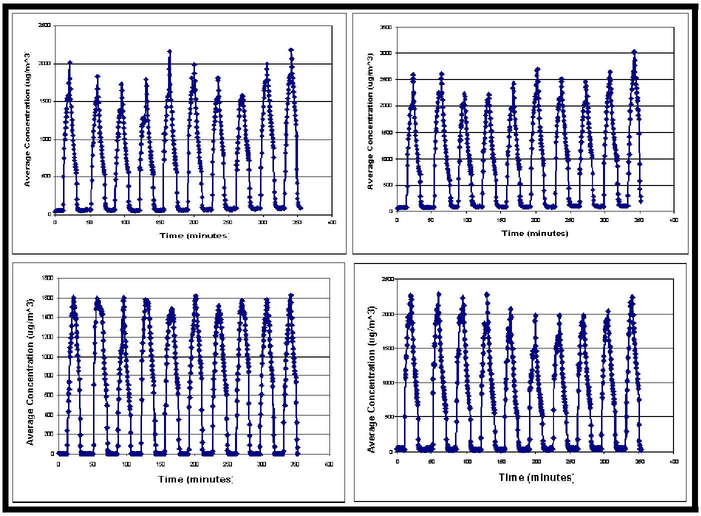

Figure 2: PM_{10} concentration for 3 cigarettes (top left); PM_{10} concentration for 4 cigarettes (top right); $PM_{2.5}$ concentration for 3 cigarettes (bottom left); $PM_{2.5}$ concentration for 4 cigarettes (bottom right).

Comparing PM_{10} graphs with $PM_{2.5}$ graphs, one can easily observe that PM_{10} concentrations were always higher than $PM_{2.5}$ concentrations, as expected. It can also be observed from the graphs that particulate matter concentration increased with the number of cigarettes burnt.

Table 1: PM_{10} and $PM_{2.5}$ emission factors.

No. of Cigarettes	PM_{10} emission factors		$PM_{2.5}$ emission factors	
	(µg/cigarette)	(µg/mg of tobacco)	(µg/cigarette)	(µg/mg of tobacco)
1	4757.69	7.32	3816.27	5.87
2	4913.94	7.56	3856.57	5.93
3	4858.04	7.47	4180.80	6.43
4	4885.03	7.52	4160.63	6.40

Table 1 summarizes $PM_{10}/PM_{2.5}$ emission factors in μg/cigarette and $PM_{10}/PM_{2.5}$ emission factors in :g/mg of tobacco. As expected, PM_{10} emitted is always more than $PM_{2.5}$ emitted. Also, $PM_{2.5}$ emissions contributed to about 84% of PM_{10} emissions.

The background concentration was subtracted from the maximum concentration when a cigarette was burnt in order to find the final concentration in $\mu g/m^3$. It is to be noted that the average concentration is the one calculated, not the one given for each sampling interval by the DataRAM.

4.2 Statistical analysis

Statistical analysis was performed to determine the relationship between $PM_{10}/PM_{2.5}$ concentrations in an enclosed test chamber and relating to the number of cigarettes. Regression analysis was performed using Quattro Pro to test the statistical significance. The overall acceptability of the regression equation was estimated using r^2 and F-test methods. The results of statistical analysis are shown on Table 2. The statistical tests showed significant relationships between the two parameters, justifying the research methodology.

Table 2: Statistical test results.

	PM_{10}	$PM_{2.5}$
Regression Equation (y*)	y = 612.63x**	y = 516.72x
Coeff. of Determination, r^2	0.93	0.97
Confidence Level, C.L.	97%	97%

*y = PM_{10} concentration in $\mu g/m^3$, **x = no. of cigarettes.

Table 3: PM_{10} emission factors comparison.

No. of Cigarettes	PM_{10} Emission Factors			
	Observed Mean (μg/cig.)	Observed Mean (μg/mg tobacco)	Estimated Value (μg/cig.)	Estimated Value (μg/mg tobacco)
1	4757.69	7.32		
2	4913.94	7.56		
3	4858.04	7.47	4839.77	7.74
4	4885.03	7.52		
Ave.	4853.67	7.47		

Another effort was made to compare $PM_{10}/PM_{2.5}$ emitted per cigarette by a simple average using regression equations developed. $PM_{10}/PM_{2.5}$

concentrations per cigarette were obtained by multiplying the regression equation by the test chamber volume. These equations are:

- $PM_{10} = 4839.77x$; and
- $PM_{2.5} = 4082.08x$, where x represents number of cigarettes.

Tables 3 and 4 summarize the values of $PM_{10}/PM_{2.5}$ emitted/cigarettes by a simple average and by regression models. $PM_{10}/PM_{2.5}$ masses emitted per cigarette are very close to the values given by the equation of regression models developed.

Table 4: $PM_{2.5}$ factors comparison.

No. of Cigarettes	$PM_{2.5}$ Emission Factors			
	Observed Mean (µg/cig.)	Observed Mean (µg/mg of tobacco)	Estimated Value (µg/cig.)	Estimated Value (µg/mg of tobacco)
1	3816.27	5.87	4082.08	6.28
2	3856.57	5.93		
3	4180.8	6.43		
4	4160.63	6.4		
Ave.	4003.56	6.17		

PM_{10} emission factors applicable to secondhand cigarette smoke, were found to be 4,840 µg/cigarette and 7.74 µg/mg of tobacco burnt. $PM_{2.5}$ emission factors were 4082 µg/cigarette and 6.28 µg/mg of tobacco burnt. Hence, it can be observed that $PM_{2.5}$ emissions contributed to about 84% of the PM_{10} emissions.

5 Conclusions and recommendations

Linear relationships between the concentrations of particulate matter (PM_{10} and $PM_{2.5}$) and the number of cigarettes used were observed. The statistical analysis coefficients (r^2 of 0.93 for PM_{10} and 0.97 for $PM_{2.5}$, and a confidence level of 97 % in both cases) support the linear relationships and validate the experimental methodology used.

Future studies should focus on other cigarette brands to study the differences in PM_{10} and $PM_{2.5}$ emissions among other brands. Due to funding and resource limitations, this study was carried out using DataRAM. Future studies should explore use of other monitoring equipment to confirm the reported emission factors and models. Emission factors should be determined for other important air toxics such as carbon monoxide, nicotine, benzene, and others. The emission factors determined are for cigarette smoke resulting from simple burning (no inhalation or exhalation by a human is included in the experiment). The results can be used to estimate the exposures to sidestream smoke (~ 80% of second-hand smoke). As the experiment did not simulate inhalation effects, the emission factors reported are conservative values. In future studies, a smoking machine may be used to simulate both sidestream and mainstream smoke emissions.

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