Combining experimental and theoretical methods to quantify indoor particulate emissions: application in an office microenvironment

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Abstract: - Particulate emissions result from the generation of new particles, the resuspension of previously settled particles and also processes that depend on particle accumulation, humidity, temperature, air velocity etc. Methods to characterize indoor particulate emissions are not well developed. This paper aims to examine experimentally particulate pollution in an office microenvironment and assess by theoretical means the relative contribution of indoor sources. Towards this aim PM_{10} and $PM_{2.5}$ concentrations were monitored during a seven days period in a typical office microenvironment in Athens Greece while outdoor PM_{10} concentrations were monitored in a nearby fixed ambient station. Then, numerical simulations with the Multi Chamber Indoor Air Quality Model were performed and the indoor particulate emissions were estimated. Results showed that hourly indoor PM_{10} and $PM_{2.5}$ concentrations reach values as high as 450 μg m^{-3} and 171 μg m^{-3} respectively. Average indoor sources were estimated to be 1200 μg min^{-1} and 3500 μg min^{-1} for $PM_{2.5}$ and PM_{10} respectively.

Key-Words: - indoor emissions, particulates, office microenvironment

1 Introduction

Due to the fact that people in the western world spend 85-90% of their time indoors, the significance of the indoor air quality is widely recognized during the last years More specifically, during the last two decades scientific studies regarding indoor air quality have focused on the key possesses that control indoor air quality such as the removal of the pollutants from the indoor environment, physicochemical processes that takes place indoors and indoor sources.

In certain cases it is convenient to assume that the change rate of the indoor concentrations is mainly governed by the outdoor pollution, the transport between the indoor and outdoor environments, deposition on indoor surfaces and indoor emissions [1]. The pollutant's transport between indoor and outdoor environment is mainly governed by the ventilation rate, which represents the tightness of the building shell, cracks, etc and depends on the pressure field inside and outside the microenvironment [2]. On the other hand processes that may occur on fixed surfaces including the heterogeneous reactions (for gases) and the direct deposition (for particles) have been often parameterized with the use of the deposition velocity (vd) [3].

Methods to characterize indoor particulate emissions are not well developed, unlike VOC emissions which are readily measurable using mass balance and chamber approaches [4]. In general, particulate emissions results from both the generation of new particles and the resuspension of previously settled particles and also processes that depend on particle accumulation, humidity, temperature, air velocity etc.

The aim of this study is to examine experimentally particulate pollution in an office microenvironment and assess by theoretical means the relative contribution of indoor sources.

2 Experiment

The experimental period was from 6/7/2005 to 14/7/2005. During the experiments PM_{10}, $PM_{2.5}$ and CO_2 concentrations indoors were measured. Details about the experimental site and the instrumentation used are given in the following.

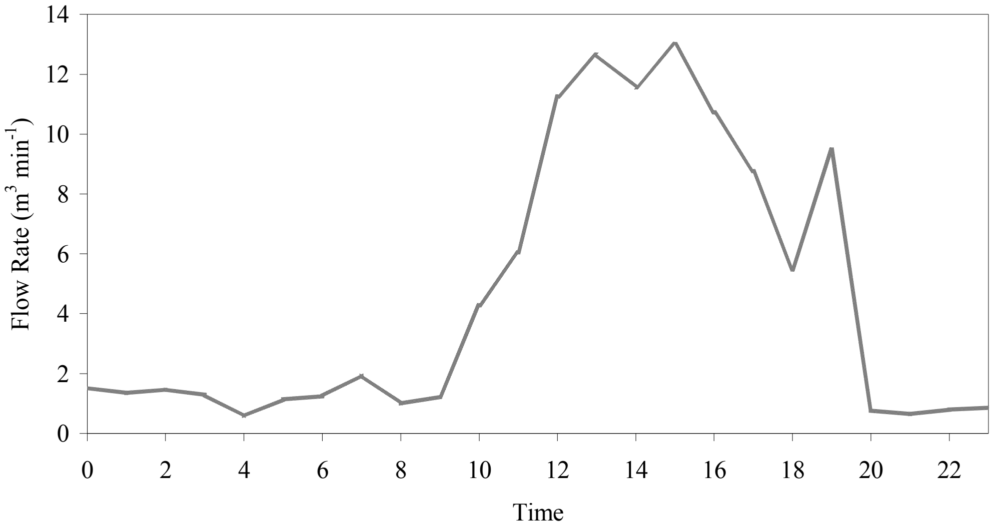

Figure 1. The average diurnal evolution of the flow rate values during working days. Details about the figure are given in the text.

2.1 Experimental site and setup

Experiments were carried out in a typical office microenvironment in the Athens Metropolitan Area. The office microenvironment is located on the third floor of a three storey building in which the technical software company 4M is accommodated. The building is located near a heavy trafficked avenue (Kifisias), which is directed in the North – South axis. In the first floor the reception of the company is situated and in the second floor there are two offices and the meeting room of the company. The third floor hosts the employees of the company. The floor is constituted by a room where the offices of the employees of the company were found, from a small kitchen where the instrumentation was placed, and finally from a small toilet. The door between the kitchen and the main room was continuously open, while the toilet door was continuously closed. During the experiments ten employees were present daily (in an 8-hour basis).

The office was ventilated by natural means (e.g. windows) and also mechanically (heating and ventilating air conditioning system). During the whole experimental period a logbook was kept recording all the activities taking place in the office, including the duration of the open windows, the number of people occupying the room and the operation hours of the ventilating system.

An indoor air quality monitor (IAQRAE of RAE systems) for CO_2 measurements was employed. The CO_2 concentrations refer to 1-hour mean values, derived from 1–min continuous measurements. The IAQRAE system provides also measurements of temperature and relative humidity, as one-hour mean values. Calibration of the instruments was performed before the beginning and after the completion of each set of measurements.

Outdoor concentrations of PM_{10} and meteorological data were collected from the air pollution monitoring station operated by the Ministry of Environment (Marousi). The station was located nearby of the office microenvironment.

During the whole experimental period a logbook was kept recording all the activities taking place in the office, including the number, the location and the duration of the open windows, the hours that the mechanical ventilation was operating, the number of the employees occupying the room, as well as the cleaning processes and hours. In order to quantify the ventilation prevailing in the office, the flow rates (m^3 min^{-1}) were calculated following the methodology presented in [5]. The methodology involves the solution of the mass-balance equation for the CO_2 concentrations, considering indoor homogeneity and negligible deposition. Outdoor CO_2 concentrations were assumed to be 1170 μg m^{-3} [1]. Indoor emission rate of CO_2 was considered mainly due to human respiration and was taken to be 589 mg min^{-1} CO_2 per person [6]. The number of employees in the office was estimated according to the logbook records.

2.2 Experimental results

In Figure 1 the average diurnal evolution (typical working day) of the flow rate during the working days is presented. During the “typical working day”, each value is the mean value of the flow rates during

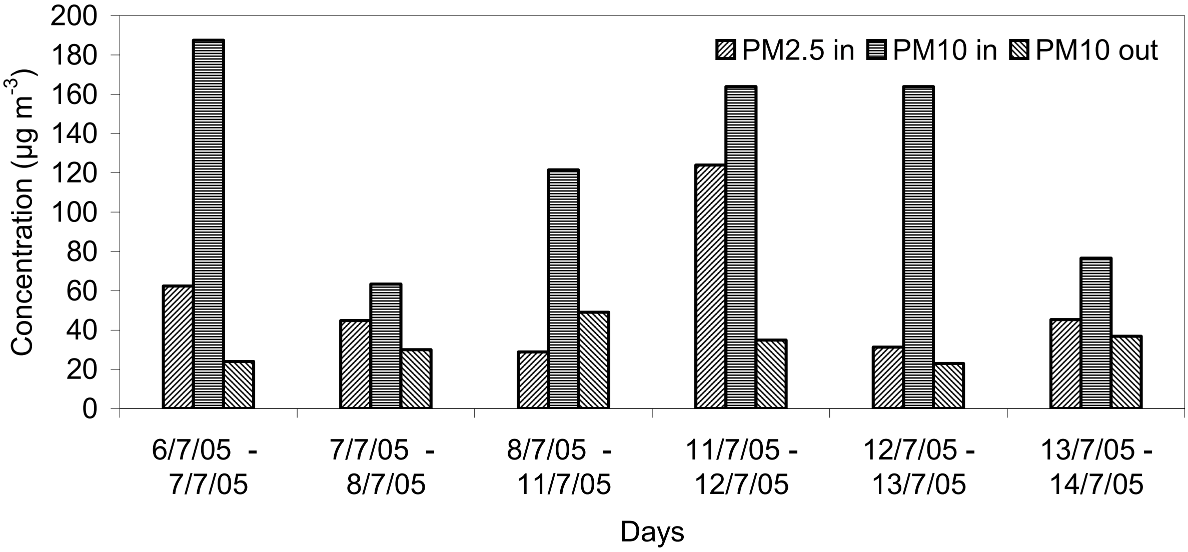

Figure 2. Measured PM_{10} and $PM_{2.5}$ indoor and outdoor concentrations

the respective hour for the whole experimental period.

It can be seen that during the night, when the windows were closed and the office was empty, the ventilation rates were at very low levels (lower than 2 m^3 min^{-1}). The same pattern presents during the early morning hours. When employees arrive and open the windows (around 10 a.m.) the ventilation progressively increases and the highest values encounters with the operation of the mechanical ventilation system. Values as high as 13 m^3 min^{-1} are observed.

In Figure 2 the measured indoor and outdoor PM_{10} and indoor $PM_{2.5}$ concentrations are presented. Indoor particulate concentrations are significantly higher than the respective outdoor ones. Indoor PM_{10} concentrations are also higher than the 24-h limit value set by the European Union (1999/30/EU) for the outdoor air (50 μg m^{-3}). The ratio of the indoor PM_{10} concentrations to the respective outdoor ones (I/O ratio not presented) is higher than unity during all experimental days. I/O ratios for a specific pollutant have been extensively used as an indicator of indoor generated pollutant [7], [8]. If the I/O ratio is greater than unity, the excess is assumed to be due to indoor emissions. Thus, in our case where I/O ratios are greater than unity during all the experimental days, intensive indoor sources are assumed. Particulate indoor production could be attributed to the continuous operation of the various equipments in the office [9], [10], and to resuspension due to the movement of the employees [4].

3 Theoretical Study

For the theoretical study of the indoor sources, the Multi Chamber Indoor Air Quality Model (MIAQ) was employed. MIAQ is a general mathematical model for both indoor aerosol dynamics and the concentrations of chemically reactive compounds in indoor air. MIAQ links a flexible description of building and ventilation system structure to a mechanistically sound analysis of particle dynamics and indoor chemistry [3], [11]. The method followed here is similar to the one described in [1].

3.1 Methodology

Consecutively numerical experiments were performed and during these experiments, the measured outdoor particulate concentrations, indoor temperature and relative humidity during a typical working day were set as input to the model. Indoor temperature of the surfaces and the geometric characteristics of the indoor surfaces were also set as inputs to the model. Indoor sources with varying strengths were simulated during the consecutive numerical experiments, until the average indoor concentrations calculated by the model were equal to the indoor measured ones.

The simulated room was considered to be a single zone occupying a volume of 187.3 m^3, with a total of 286 m^2 surfaces (ceiling, floor and walls). Ventilation of the simulated room was calculated with the method presented in section 2. Two aerosol size ranges were considered: one is 0.1-2.5 μm and accounts for $PM_{2.5}$ and the second 2.5-10 μm stands for PM_{10} - $PM_{2.5}$. Outdoor values of PM_{10} that were used as an input during the model simulations were measured at a fixed ambient station operated by the Ministry of Environment (see section 2). The corresponding outdoor concentration values for $PM_{2.5}$ were considered to be at 60% of PM_{10} values since outdoor particulates were mainly associated with automobile combustion [12], [13]. The efficiency at which particles are removed by the mechanical ventilation system was considered to be 0.1 (10% of the entering particles were removed by the mechanical ventilation system)

During the numerical experiments it was considered that indoor particles were controlled by the interplay of ventilation, deposition, coagulation and indoor sources. The iteration step was set to 1 minute and there were 30 iteration steps in order to have the concentration results.

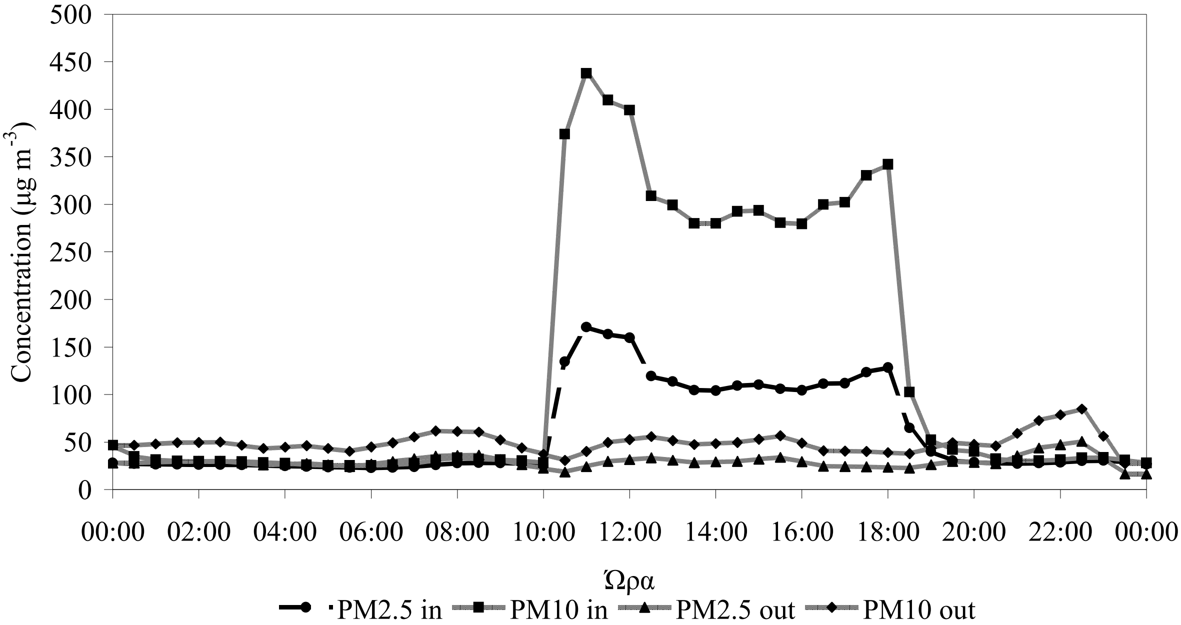

Figure 3. Measured PM_{10} and $PM_{2.5}$ indoor and outdoor concentrations

3.2 Results

In Figure 12 the time evolution of the simulated indoor PM_{10} and $PM_{2.5}$ concentrations along with the measured outdoor PM_{10} and estimated $PM_{2.5}$ ones during a typical working hours are presented. The time evolution of the simulated indoor PM_{10} and $PM_{2.5}$ concentrations revealed that indoor PM_{10} and $PM_{2.5}$ concentrations reach extremely high values compared to the corresponding outdoor values, indicating the importance of the indoor emitted particulates during the working hours. The highest indoor concentrations are observed during the working hours, reaching values as high as 450 μg m^{-3} and 170 μg m^{-3} for PM_{10} and $PM_{2.5}$ concentrations respectively. The particulate levels were reduced substantially (below 50 μg m^{-3}) when the room was evacuated and the ventilation permitted fresh outdoor air to enter indoors.

According to the numerical experiments described, an average of about 1200 μg min^{-1} of $PM_{2.5}$ and a total of about 3500 μg min^{-1} of PM_{10} are emitted in the indoor environment. The estimated emission rates account for the direct particulate emissions due to the various operations conducted within the experimental room, but also include re-suspension. It is interesting to notice that in [4] it was found that fine particles do not correlate with occupant activities such as walking. Thus the $PM_{2.5}$ emissions found here may be attributed mainly to the equipment operation and in [9] and [10] it was found that particulates resulting from printer operations in offices are mainly in the ultrafine mode while contribution to coarse mode particles is less important. According to [4] an average of 10 μg m^{-3} per person should be expected due to resuspension from the persons movement. In the frame of the methodology presented here there can be no distinction between the two major sources contributing to indoor emissions.

It should be noticed that processes such as the nucleation and condensation were included in the source term [11].

The methodology described here is valid under certain assumption the main of which are: (1) values of the outdoor PM_{10} concentrations measured from the fixed ambient station and taken into consideration during the numerical simulations, are the same of those that encounter in the immediate outdoor environment of the office microenvironment. (2) outdoor $PM_{2.5}$ concentration are 60% of the respective PM_{10} values. (3) aerosols are inert i.e. condensation/evaporation and nucleation are negligible when compared to other aerosol processes. (4) no intense gradients are present in the indoor environment

4 Conclusion

A combination of experimental and theoretical methods was applied in order to quantify indoor particulate emissions. The source estimation gave an average of 1200 μg min^{-1} of $PM_{2.5}$ and a total of about 3500 μg min^{-1} of PM_{10} emitting in the indoor environment either by direct indoor sources or by resuspension. Furthermore it was found that indoor concentrations reach extremely high values exceeding by far limits set by international organizations.

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