Examining the relative contribution of ventilation and deposition rates on indoor SO_2 concentrations

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Abstract: - In this study the relative contribution of ventilation and deposition rates that control the levels of indoor SO_2 concentrations in three indoor residential microenvironments with different characteristics were examined. The air quality in the three microenvironments was experimentally studied by probing the indoor and outdoor SO_2 concentrations. The microenvironments were also theoretically examined with respect to the temporal evolution of indoor SO_2 concentrations by constructing a "typical day", with the aid of the Multi Chamber Indoor Air Quality Model. The model-predicted indoor concentrations are in fairly good agreement with the measured values. From the data obtained during the model simulation, the relative contribution of the transport and deposition mechanisms to the variation of the indoor concentrations was examined. It was found that indoor SO_2 variation rates mainly depend upon the interplay between the transport from the outdoor environment and the deposition upon surfaces, while the transport from indoor to outdoor seems to be insignificant.

Key-Words: - indoor air quality, ventilation, deposition, apartments

1 Introduction

Scientific interest with respect to indoor exposure has intensified during the last decades. due to the fact that people spend more than 90% of their time indoors. Intensive scientific research has concluded that pollution in the indoor environment may originate either from indoor sources, such as cigarette smoking [1], [2], [3], combustion devices, cooking and cleaning [2], or from outdoor pollution that penetrates through the ventilation system [4], [5]. Recently, scientific research has focused on the key possesses that control indoor air quality such as the pollutants' entering and removal from the indoor environment through ventilation and also heterogeneous physicochemical processes which are generally parameterized as deposition of the gaseous species on indoor surfaces.

In many cases it can be assumed that the change rate of the indoor concentrations is mainly controlled by the outdoor pollution, the transport between the indoor and outdoor environments and deposition on indoor surfaces [6]. Each of these processes can be described by a characteristic parameter, called hereafter "controlling parameter". The controlling parameter of the pollutant's transport between indoor and outdoor environment is the ventilation rate, which represents the tightness of the building shell, cracks, etc and depends on the pressure field inside and outside the microenvironment [7]. On the other hand processes that may occur on fixed surfaces including heterogeneous reactions for gases have been often parameterized with the use of the deposition velocity (vd) and the controlling parameter is the deposition rate [8].

The aim of this study is to examine the relative effect of the transport between the indoor and outdoor environment and the heterogeneous chemistry between SO_2 and indoor surfaces in different apartmental microenvironments.

2 Experimental Sites and Setup

The experimental campaign was carried out in three residential apartments (hereafter called microenvironments) in the city of Athens, Greece. Microenvironment 1 (ME1) is located in a residential area close to the historical centre; microenvironment 2 (ME2) is located close to a major traffic route, while microenvironment 3 (ME3) is located in a purely residential area (Figure 1). The apartments have different characteristics (

dimensions, size, etc.) as well as different ventilation patterns that will be discussed in the next section. The experiments covered two different time periods of the year (warm and cold) in order to address questions regarding seasonal variability. The period from October to April was considered as the cold period of the year while May to September the warm period. During the experimental periods a logbook was kept recording all the activities taking place in the apartments including the duration of the open windows, the number of people occupying the room.

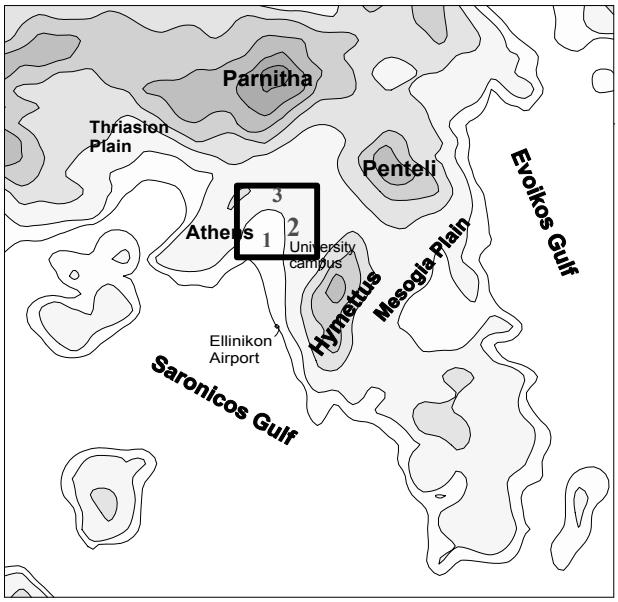

Figure 1. The Greater Athens Area. Numbers indicate the location of the apartmental microenvironments.

The instrumentation used for the measurements of SO_2 was a 360 Series - Horiba Analyzers. The analyzer was interfaced to a three - port valve that alternated sampling between indoors and outdoors on a 15-minute cycle. A series of measurements of ventilation rate was performed at each house by means of the inert gas (SF_6) decay-time method. Indoor temperature and relative humidity were measured at a height of 1.2 m, using a small stand. Also, the differential pressure between the indoor and outdoor environment was measured, while air quality data from the fixed air quality monitoring stations of the Ministry of Environment were employed.

Calibration of the instruments was performed before the beginning and after the completion of each set of measurements. The calibration of the instruments was performed using gas cylinder, containing unmixed (pure) air for the zero calibration and 0.84 ppm concentration of SO_2 for the span calibration.

3 Experimental results

In Figure 1 the diurnal evolution of the SO_2 indoor and outdoor concentrations at ME1 during the cold period is presented. The diurnal evolution corresponds to a "typical day" and the hourly concentrations are the mean value of the respective measured concentrations for each hour of day, for all the experimental days. It can be seen that indoor concentrations closely track the outdoor ones with a small time lag (clearly observed at 19:00). Analogous results were obtained for the other microenvironments but are not presented for reasons of brevity.

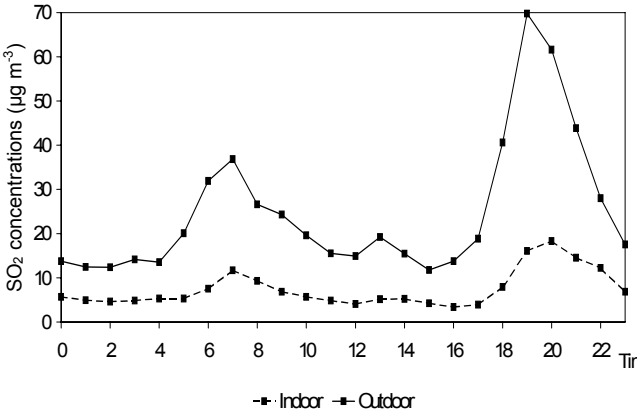

Figure 2. Indoor and outdoor average diurnal evolution of SO_2 concentrations at ME1 during the cold period.

Report of the measured ventilation rates can be found in [9]. It was found that the most "tight" apartment with respect to the ventilation rate was ME3 during both the cold and warm experimental periods (average ventilation rates 0.4 h^{-1} and 0.5 h^{-1} respectively), with ME1 being the least sealed (average ventilation rates 0.7 h^{-1} and 1.4 h^{-1} during the cold and warm period respectively). Generally the ventilation rate is higher during the warm than the cold period.

The deposition rates were calculated using the methodology described in [9]. Reports of the calculated deposition rates can be found in the same paper. In general SO_2 deposition rates ranged between 0.2 h^{-1} and 3.2 h^{-1} depending on the different construction characteristics, variations in relative humidity and differences in furnishings during the different periods.

4 Model Applications

Having obtained the above-mentioned experimental data, the application of a numerical model that predicts the indoor concentrations for air pollutants was possible. The model selected was the Indoor Multi-Chamber Indoor Air Quality Model (MIAQ), a general mathematical model which is used to compute both indoor aerosol dynamics and the concentrations of chemically reactive compounds in indoor air. It accounts for heterogeneous removal, and photolytic and thermal chemical reactions for reactive gasses. Model results were repeatedly validated against experimental data [10], [11], [12], [13].

During the model application, the following were taken into consideration: (1) for each experimental period, a "typical day" was constructed as described above. The concentrations that were taken into consideration correspond to periods that the windows were closed. The daily evolution of the outdoor concentrations during a “typical day” was set as input to the model (2) The ventilation rate at each experimental period was the mean value of the measured ventilation rates as reported in [9]. (3) The deposition velocities were the deposition velocities reported in [9]. (6) During the simulations SO_2 was treated as chemically inert. Thus, the mechanisms that control the indoor SO_2 concentrations are the transport between indoors and outdoors and the deposition.

In Figure 3 the "typical day" of the SO_2 concentrations during the cold period at ME1 as resulted from the measurements and predicted by the model, is presented. In the same figure, the standard deviations of the measured concentrations are also shown. The agreement between the measured and predicted concentrations is satisfactory. Similar results were obtained for all pollutants during the cold and warm periods at all microenvironments (not shown for reasons of brevity). In Figures 4 scatter plots between the measured and predicted concentrations are presented, and in Table 1 quantitative measures between the measured and predicted concentrations are also presented.

The quantitative measures are: the mean value and standard deviation of the measured ($\bar{O}$ and sd(O)) and model predicted ($\bar{P}$ and sd(P)) concentrations respectively, the mean absolute error (MAE) between the observed and model predicted concentrations, the root mean square error (RMSE) between the observed and model predicted concentrations, its systematic (RMSEs) and unsystematic (RMSEu) portion, the index of agreement (d) and the correlation coefficient (R) Details concerning the quantitative measures can be found in [13].

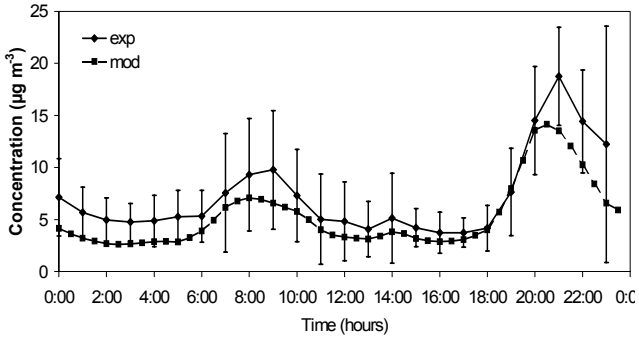

Figure 3 "Typical day" of the SO_2 concentrations, as resulted from measurements and predicted by model. Error bars correspond to the measured standard deviation of indoor concentrations.

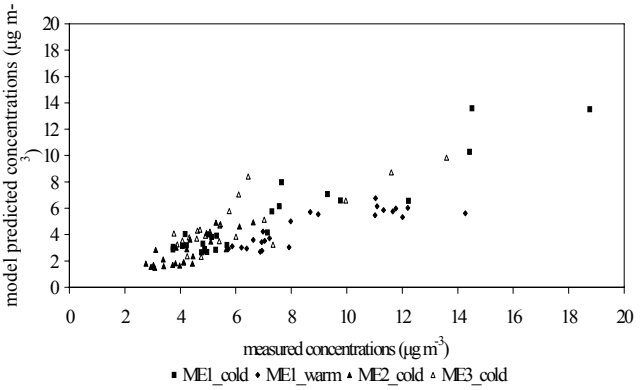

Figure 4: Scatter plot of measured and predicted SO_2 indoor concentrations.

As can be seen from Table 1 and Figure 4, the correlations between the measured and predicted concentrations and the indexes of agreement are satisfactory. The correspondence is also good when comparing the mean values. The systematic portion of the root mean square error is greater than the unsystematic portion. This observation in conjunction with the observation that predicted values are lower than the measured ones may indicate that the calculated deposition rates are somewhat higher than the real values.

It should be mentioned that deviations of the model predicted indoor concentrations from the measured values should be expected in some cases due to a variety of reasons, and mainly due to the fact that during the simulations only average values of all input parameters (outdoor concentrations deposition velocity, ventilation rates) were considered.

Table 1: Quantitative measures of MIAQ model performance. The terms *N, d* and *R* are dimensionless, while the remaining terms have the units μg m^{-3}

N	$\bar{O}$	$\bar{P}$	*sd(O)*	*sd(P)*	*R*	*d*	*MAE*	*RMSE*	$RMSE_s$	$RMSE_u$
96	6.59	4.30	3.17	2.29	0.83	0.79	2.36	2.9	2.61	1.26

It is evident though that in some cases temporal fluctuations may introduce errors in the time averaged values [14]. Nevertheless, from Table 7, it becomes evident that the average values obtained from the model calculations give a fairly good representation of the indoor concentrations in the different microenvironments.

The assessment of the relative contribution of the main mechanisms that control indoor air quality is given by means of the source and sink rates due to the different mechanisms, given as a MIAQ-model output [15] in μg min^{-1}. In particular we investigated:

- The rate by which the pollutants are transported from the outdoor environment indoors through ventilation (transport source)
- The rate by which the pollutants are removed from the indoor environment through the same mechanism (transport sink)
- The rate by which the pollutants are removed from the indoor air due to deposition onto indoor surfaces (deposition)
- In Figure 5 the mean source and sink rates of the various mechanisms at the three microenvironments during the cold and warm periods are presented, and in Table 2 the statistical values of the calculated source and sink terms are shown. It can be seen that indoor SO_2 variation rates mainly depend upon the interplay between the transport from the outdoor environment and the deposition upon surfaces, while the transport from indoor to outdoor seems to be insignificant. The high deposition velocities observed in ME1 during the cold period (in Table 4) lead to high values of the sink term due to deposition.

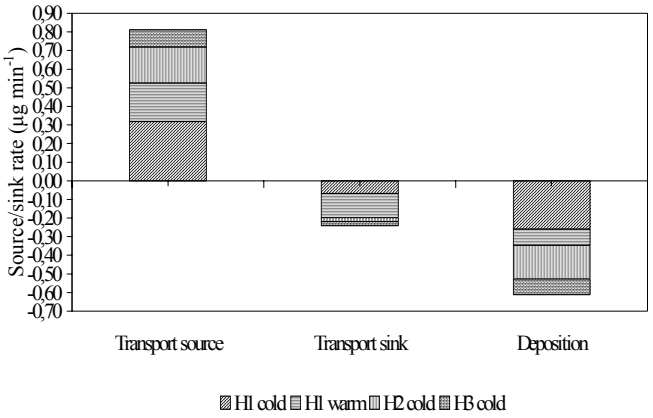

Figure 5: Mean source and sink rates of SO_2 indoor concentrations due to the various mechanisms at the three microenvironments during cold and warm periods.

Table 2: Statistical values of the model calculated source and sink terms due to the various mechanisms (in μg min^{-1}).

	mean	min	max
transport source	0.2	0.092	0.320
transport sink	0.046	0.021	0.129
deposition	0.134	0.084	0.26

In general the source and sink rates depend upon the combined action of the outdoor (regarding the source terms) and indoor (regarding the sink terms) concentrations and the controlling parameter of each mechanism. For example, the source rate due to transport from the outdoor environment indoors depends on the ventilation rate and the outdoor concentrations, while the sink rate due to deposition depends on the deposition rate and the indoor concentrations. In this case, the controlling

parameters of the mechanisms that were taken into account (ventilation rate for the transport between indoors and outdoors and deposition rate for the deposition indoors) have constant values. Thus, the temporal evolution of the source and sink rates depend on the respective temporal evolution of the outdoor and indoor concentrations. On the other hand the variation of the source and sink terms between the different microenvironments depend on the variation of both the controlling parameters and the

4 Concluding remarks

The air quality in three apartmental microenvironments was experimentally studied by probing the indoor and outdoor SO_2 concentrations and also theoretically examined with respect to the temporal evolution of SO_2 concentrations in the indoor environment throughout a 24-hour period, with the aid of the Multi Chamber Indoor Air Quality Model. The model-predicted indoor concentrations are in fairly good agreement with the measured values. The relative contribution of the transport and deposition mechanisms to the variation of the indoor concentrations was examined. The source and sink rates due to transport and deposition mechanisms depend on the combined action of the outdoor and indoor concentrations and the controlling parameter of each mechanism. Thus, high indoor levels were always accompanied with high outdoor concentrations under high or moderate ventilation. It was also found that temporal evolution of the source and sink rates depend on the respective temporal evolution of the outdoor and indoor concentrations

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