Statistical analysis of parameters influencing the relationship between outdoor and indoor air quality

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ABSTRACT

Within the framework of the French national research program PRIMEQUAL, measurements of outdoor and indoor pollution have been carried out in eight schools of La Rochelle (France) and its suburbs. The buildings were naturally ventilated by opening the windows or mechanically ventilated, and showed various air permeabilities. Ozone, nitrogen oxides (NO and NO_2), and particles (15 size intervals ranging from 0.3 to 15 μm) concentrations were continuously monitored indoors and outdoors for two 2-week periods. The indoor humidity, temperature, CO_2 concentration (occupancy), window opening and building permeability were also measured. The paper deals with a statistical analysis of the data aimed at identifying the parameters influencing the compared outdoor and indoor pollution levels. After a brief description of the experimental data, the results of the principal component analyses (PCA) are discussed by referring to the likely underlying physical processes involved. The main conclusions arising from the study are: (1) the influence of occupancy on indoor particle concentrations varies as a function of the particles size; (2) the building permeability greatly influences the indoor/outdoor concentrations ratio for ozone and (3) the method enables one to identify the cases where nitrogen oxides are emitted indoors.

INDEX TERMS

Indoor/outdoor pollution; Building permeability; Schools; Statistical analysis

INTRODUCTION

Contaminant transport in buildings involves a variety of more or less complex phenomena including advective transports, indoor sources, chemical reactions in the bulk air phase of the rooms, and heterogeneous processes at the air and solid interfaces (Blondeau *et al.* 1996). During the past 30 years, several studies have dealt with the influence of outdoor pollution on indoor air quality. Many of them were based on simultaneous measurements of outdoor and indoor contaminant concentrations in naturally ventilated or air-conditioned buildings (Phillips *et al.*, 1993; Chao, 2001; Kirchner *et al.*, 2001), and the results were often discussed in terms of 'contaminants transport from outdoors to indoors' or 'entering of atmospheric pollution indoors'. However, such names may be confusing as they suggest that the phenomenon investigated only relates to advective transports while the measured indoor concentrations include the effects of all the phenomena listed above. Due to possibly great differences in the contribution of these phenomena from one building to the other, the consequence is that the calculated indoor to outdoor concentration ratios (I/O) vary in a very wide range without any explanation on the reasons of the measured values. The present paper aims at improving the knowledge on this topic by identifying the factors that may influence the indoor to outdoor concentration ratios of contaminants originally contained in the outdoor air. Particular emphasis is laid on the role of the building air permeability, which determines the ventilation airflow rate of the building (advective transports) but also the residence time of the air inside buildings. The latter gives the time available for homogeneous and heterogeneous processes to occur (Weschler and Shields, 2000). The paper first presents a

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brief description of the experimental data. Then, the correlations shown by principal component analysis (PCA) diagrams are synthesized and discussed by referring to the likely underlying physical phenomena.

EXPERIMENTAL DATA

Within the framework of a study of the French national research program on atmospheric pollution PRIMEQUAL, the outdoor and indoor concentrations of ozone (O_3), nitrogen oxides (NO and NO_2), and particles (particles count within 15 size intervals ranging from 0.3 to 15 μm), as well as the indoor humidity, indoor temperature, building occupancy (CO_2 indoor concentration), and window opening of the experimental room, were continuously monitored in eight schools of La Rochelle (France) and its suburbs. The experiments were carried out for two 2-week periods in each school, one during winter and the other one during spring or summer. The buildings permeability was also measured using a two-step procedure. First, the coefficient C_s ($m^3\ h^{-1}\ Pa^{-n}$) and exponent n of the permeability law,

$$Q = C_s \Delta P^n \quad (1)$$

where Q ($m^3\ h^{-1}$) is the air flow rate penetrating through the building envelope when a pressure difference across the building envelope ΔP (Pa) exists, were determined using the so-called DC pressurization technique (Limb, 1992).

Then, the building permeabilities were assessed by calculating the air flow rate under the conventional 4 Pa reference pressure difference (Table 1).

As Table 1 shows, the schools were selected with a view of diversity in their location, ventilation and airtightness. In the case of school Lavoisier, the windows were changed between the first and second measurements series, resulting in a decreased air permeability of the building envelope. Consequently, the two series are named Lavoisier and Lavoisier R (for renovated) instead of Lavoisier W (for winter) and Lavoisier S (for summer or spring) as for the other schools. Considering the calculated permeabilities, the schools may be classified into three broad groups of permeability—low, medium and high (Table 1). Due to unexpected hidden air paths between the rooms of schools Laleu and Valin, no permeability measurement could be performed; the fan was not powerful enough to generate high enough pressure differences across the room envelope. However, based on a visual analysis of the building and openings, these schools were assumed to be airtight. Considering the results of the correlation analysis presented in the following section, this assumption seems to be relevant.

A detailed presentation of the experimental facility and results can be found in Blondeau *et al.* (2002). As a summary of the information obtained, Table 2 presents the mean indoor and outdoor concentration ratios over the 2-week periods for ozone, nitric oxide, nitrogen dioxide and particles (three different size intervals are considered). NO and NO_2 concentration ratios greater than unity in schools Laleu and Esnandes suggest that these compounds are emitted indoors. Investigation in the measurement places concluded that the phenomenon may originate from a bad connection between the boiler and the flue. In the specific case of school Laleu, it may also be due do smokes partially re-entering the building after being emitted outdoors (the chimney was located close to the experimental classroom). Consequently, the measured outdoor concentrations would not correctly represent the mean pollution level in the outdoor air surrounding the room. Except these two particular cases, Table 2 shows I/O ratios which are on the whole greater for nitrogen dioxide than for nitric oxide, the latter being greater than for ozone: the I/O ratios vary in a range from 0 to 0.45 for ozone, from 0.5 to 1 for nitric oxide and from 0.88 to 1 for nitrogen dioxide. Given that ozone is known to be highly reactive, there is little doubt that lower I/O ratios for ozone than for nitrogen oxides result from a stronger destruction of ozone in the indoor air rather than differences in the filtering of the ventilation air when entering the building envelope.

Table 1 Main features of the schools and rooms selected

School	Location	Ventilation	Windows	Measured permeability $Q_{4\,Pa}$ (m^3/h)
Laleu	Near industrial area	Window opening	PVC, undamaged	No measurement (supposed low)
Lafond	Close to high traffic avenue	Window opening	PVC, undamaged	0 (low)
Lavoisier	Residential area	Window opening	Wood damaged	156 (medium)
Lavoisier R			PVC, undamaged	3 (low)
Descartes	Seaside	Window opening	Metal, damaged	292 (high)
Dor	City centre	Window opening	PVC, undamaged	4 (low)
Valin	City centre	Window opening	Wood, undamaged	No measurement (supposed low)
St-Xandre	Small town in the suburb	Mechanical	PVC, undamaged	146 (medium)
Esnandes	Small town seaside	Mechanical	Metal, undamaged	156 (medium)

Table 2 Mean indoor and outdoor concentration ratios (I/O) over the 2-week measurement period

School	O_3	NO	NO_2	PM 0.3–0.4 µm	PM 1–1.6 µm	PM 5–7.5 µm
Descartes S	0.4	0.76	0.9	1.12	1.73	4.46
Descartes W	0.45	0.57	0.93	0.58	1.76	4.97
Lavoisier	0.14	0.5	0.88	0.7	1.9	9
Lavoisier R	0.15	0.57	0.87	0.88	1.07	3.93
Lafond S	0.28	0.98	0.93	1.11	2.76	4.12
Lafond W	0.08	0.87	0.9	0.69	1.81	1.8
Laleu S	0.14	1.85	1.12	1.12	1.26	3.06
Laleu W	0.08	2.59	1.03		No data	
Dor S	0.00	1.27	1.17	0.66	0.41	0.15
Dor W1	0.11	No data		0.49	0.60	1.54
Dor W2	0.00	1.07	0.88		No data	
Esnandes S	0.15	19.68	8.94	0.73	1.04	2.31
Esnandes W	0.25	1.10	1.01	0.41	0.68	2.16
St-Xandre S	0.23	0.89	0.88	1.13	0.97	3.33
St-Xandre W	0.28	0.97	0.94	1.18	1.05	4.02
Valin S	0.05	0.94	0.96	0.66	0.77	1.77
Valin W	0.25	0.97	0.97	0.86	1.03	12.16

Contrary to gaseous contaminants, most of the I/O ratios for particles are greater than unity and except the series Dor S, the larger the particles are the higher are the ratios. As indoor particle concentrations are strongly correlated with occupancy (see the following section), the explanation is probably the re-suspension of previously deposit particles when the room is occupied. The larger the particles, the heavier they are and the easier they get deposited on the floor or furnishings. Consequently, the influence of re-suspension on the indoor particle concentration, and the I/O ratio, increases with the particle size. The fact that Dor S is the only series where the experimental room remained unoccupied through out the experimental period

is in line with this assumption. Further evidence of its relevance was given by comparing the ratios calculated during the occupation and non-occupation periods of the experimental room (Blondeau *et al.*, 2002).

CORRELATION ANALYSIS

Correlation between indoor contaminant concentrations and the other measured parameters was investigated using principal component analyses (PCA) (Jackson, 1991). Mean daily values were considered for the analysis. Table 3 shows a synthesis of the PCA diagrams visual analysis. It indicates whether a direct correlation (D), an inverse correlation (I) or no correlation (0) was found between the two parameters reported in the first row of the corresponding column. Direct correlations represent cases where the values of the first and second parameters vary in the same direction (the second parameter increases as the first one increases and vice-versa) while inverse correlations represent cases where they vary in opposite directions.

The first columns of Table 3 present the observed correlations between the measured indoor and outdoor contaminant concentrations. Except the cases where an internal emission occurred (Laleu and Esnandes), the PCA diagrams show direct correlation for nitrogen oxides. It indicates that the indoor NO_x concentration levels mainly depend on the corresponding outdoor concentration levels. The situation is different in the case of ozone where direct correlations are observed for the less airtight buildings and no correlation can be noted for the airtight schools. In the latter case, the indoor ozone concentrations are close to zero, which means ozone is removed from the bulk air of the rooms and emphasize the great influence of homogeneous reactions and/or heterogeneous processes at the solid interfaces. The more airtight the buildings are, longer is the residence time of the ventilation air indoors, hence longer is the time available for homogeneous and heterogeneous processes to occur, and finally the lower the indoor ozone concentration.

In the case of particles, different correlations may be noted depending on the particles size: while direct correlations are predominant in the size interval 0.3–0.4 μm, almost any correlation can be found for slightly larger particles (2.0–3.0 μm). At the same time, Table 3 shows a predominance of direct correlations between carbon dioxide and indoor particle concentrations in the size interval 2–3 μm, but seldom correlations between the two variables in the size interval 0.3–0.4 μm. It can be concluded that the influence of occupancy on the indoor particle pollution varies as a function of the particles size. In the case of small particles, the indoor pollution level mainly depends on the particle transports from outdoors. As mentioned in the previous section, larger particles deposit more quickly on surfaces, and re-suspension due to human activity becomes the leading phenomenon of the contaminant transport indoors.

Table 3 Synthesis of correlation relations observed from the PCA diagrams

School	Series	O_{3i}/O_{3o}	NO_i/NO_o	NO_{2i}/NO_{2o}	PM_i/PM_o (0.3–0.4 μm)	PM_i/PM_o (2–3 μm)	CO_{2i}/O_{3i}	CO_{2i}/NO_i	CO_{2i}/NO_{2i}	CO_{2i}/PM_i (0.3–0.4 μm)	CO_{2i}/PM_i (2–3 μm)	NO/NO_2		NO_2/O_3		NO/O_3		O_3/PM	
												i	o	i	o	i	o	i	o
St-Xandre	Summer	D	D	D	0	D	I	0	0	D	D	D	D	0	0	0	0	I	I
	Winter	D	D	D	D	0	I	D	D	D	D	D	D	I	I	I	I	I	I
Lavoisier	Renovated	0	D	D	D	0	0	0	D	0	D	0	0	0	I	0	0	0	0
	Winter	0	D	D	D	0	I	D	D	0	D	D	D	0	I	I	I	0	0
Lafond	Summer	D	D	D	D	0	0	D	0	0	/	0	0	0	0	I	I	0	0
	Winter	0	D	D	D	0	/	/	/	/	D	D	D	0	0	0	0	0	I
Descartes	Summer	D	D	D	D	D	0	0	0	0	D	D	D	0	0	0	0	I	I
	Winter	D	D	D	D	0	0	0	0	0	D	D	D	0	0	I	I	I	I
Dor	Summer	0	D	D	D	D	0	0	D	0	0	0	0	0	0	0	0	I	0
	Winter (1)	0	/	/	D	0	/	/	/	D	D	/	/	/	/	/	/	0	I
	Winter (2)	0	D	D	/	/	/	/	/	/	/	D	D	I	I	I	I	/	/
Valin	Summer	0	D	D	0	0	0	0	0	D	D	D	D	0	I	0	I	0	I
	Winter	D	D	D	0	D	0	0	0	0	0	0	0	0	0	I	I	0	0
Laleu	Summer	0	0	0	D	D	0	0	0	D	D	0	0	0	0	I	0	0	0
	Winter	0	0	D	/	/	/	/	/	/	/	0	D	0	I	I	I	/	/
Esnandes	Summer	0	D	0	D	0	D	0	0	0	D	0	0	0	0	0	0	0	0
	Winter	D	0	0	D	D	0	0	0	0	D	0	0	0	0	0	0	0	0

Legend*: 0, no correlation found; D, direct correlation; I, inverse correlation; /, no data; i, indoor environment; o, outdoor environment.*

Considering that the building occupants offer additional surfaces for potential heterogeneous processes, one may think that occupancy could also influence the indoor concentrations of gaseous contaminants. However, Table 3 does not present any significant correlation between these concentrations and the indoor CO_2 concentrations. On the other hand, Table 3 shows many cases where inverse correlations exist between the indoor ozone and particle concentrations. It suggests that a significant amount of ozone may be removed at the particles surface.

Finally, Table 3 enables one to demonstrate the influence of indoor ozone, nitric oxide and nitrogen dioxide on their own concentration level due to chemical reactions in the bulk air-phase. Direct correlation relations between NO and NO_2, and inverse correlations between O_3 and NO and O_3 and NO_2, are observed, which is in agreement with what is now well known in the field of atmospheric chemistry.

CONCLUSION

The database presented in this paper contains simultaneous measurements of indoor and outdoor contaminant concentrations as well as some information on other parameters which influence on IAQ has been investigated using principal component analyses. The measured I/O concentration ratios agree with the results of previous studies and may be useful to assess the children exposure to indoor pollution based on outdoor pollution data. The results of the correlation analysis enables one to get more accurate information on IAQ in specific cases by identifying measurable parameters that influence the indoor concentration levels, or the related I/O ratios. Such information is also a first step in developing stochastic models aimed at predicting IAQ from outdoor pollution data.

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