Distribution of room air contaminant concentrations as a function of ventilation and air cooling—a numerical investigation

Andrei Damian[a,b,*], Patrice Blondeau[b], Francis Allard[b]

[a]*Technical University of Civil Engineering, Bucharest, Romania;* [b]*LEPTAB, University of La Rochelle, France*

ABSTRACT

The paper deals with a numerical investigation of the influence of ventilation and air conditioning on the distribution of pollutant concentrations in buildings. The model used is a coupled thermal and airflow model where the room is divided into 18 sub-zones. Temperatures and pressures are determined from the mass and energy conservation equations in each sub-zone, while airflow rates between two adjacent sub-zones are determined from the Bernoulli equation. The model also considers the so-called sink effect of the walls by including equations for boundary layer diffusion, diffusion in the pores of building materials and adsorption/desorption at the solid interfaces.

The room concentration profiles and occupants's daily exposure have been determined for two acetone sources and three different ventilation and air conditioning systems. First, the impact of the wall and acetone interactions on the predicted occupants' exposure is demonstrated by comparing the indices calculated when these interactions are considered and when they are not. Then, the paper focuses on the case of displacement ventilation with supply air containing the contaminant. Particular emphasis is put on demonstrating how the location of the contaminant source may influence the concentration distribution in the room air and the resulting ventilation effectiveness.

INDEX TERMS

Sink effect; IAQ modelling; Airflow pattern; Exposure assessment; Ventilation system

INTRODUCTION

During the past 15 years, considerable progress has been made in the field of indoor air quality modelling and simulation has become an important tool when designing ventilation systems, defining ventilation and air conditioning strategies, or assessing ventilation efficiency. Different models may be used to predict IAQ: CFD models are based on the resolution of Navier–Stokes equations over a very fine grid dividing the room volume. They can accurately handle complex problems but are computationally intensive. On the other hand, single zone or multizone models considering a perfect mixing of the room air require little computational time but cannot deal with the influence of the airflow pattern on IAQ. Finally, zonal models are simplified tools that can be seen as a good deal between CFD and single zone or multizone models. Such a model was used in the present study to investigate the influence of different ventilation and cooling systems on the contaminant distribution in an office-type room. As most gaseous pollutants found in indoor spaces may interact with building materials and furnishings, these phenomena are often neglected in IAQ simulation tools, combined sorption and diffusion transport models in the building walls when implemented. By comparing the occupants' exposure that were computed with and without considering these interactions, the first part of the paper enables one to assess the contribution of the so-called sink effect to the predicted mean indoor pollution level. Then, the second part of the paper focuses on the specific case of displacement ventilation. Simulations were carried

[*] Corresponding author.

out to characterize the contaminant concentrations' heterogeneity within the room air when the contaminant is emitted indoors by the supply air.

METHODS

The simulation tool used to carry out the case studies presented hereafter is a coupled thermal, airflow and IAQ simulation tool based on the concept of zonal modelling. It was developed in the SPARK environment (Ayres Sowell, 1997). The model considers the room volume is divided into 18 discrete control volumes or cells (also called sub-zones). The air is assumed to be perfectly mixed within these cells: temperature, pressure and contaminant concentrations are uniform and determined from a set of equations including the mass balance equations (air, contaminants) in each sub-zone, the thermal balance equations in each sub-zone and the gas state equations. Each sub-zone i is linked with adjacent sub-zones j (with a total number of six in the three directions of space Ox, Oy and Oz) by flow elements called air interfaces (vertical or horizontal interfaces). The airflow passing through these interfaces are calculated using the Bernoulli equation (Musy, 1999). In the regions where dominant flows take place (ventilation jets, thermal plumes or boundary layer flows) specific equations are used: the cell is split into a well mixed sub-cell and a driven flow sub-cell, each of them being governed by its specific set of equations.

The reference room considered for the simulations is an office-type room of 5 m length (direction Ox), 5 m width (direction Oy) and 2.8 m height (direction Oz). It has one external wall facing west and seven internal walls including ceiling, doors and floor being in contact with rooms whose temperature and concentrations are assumed to be always the same as in the reference room. This assumption was made in order to make the analysis easier as it eliminates the influence of thermal and contaminant conditions in adjacent rooms on the temperatures and concentrations predicted in the reference room. The external wall, ceiling and floor are assumed to be constructed of 15-cm-thick concrete, while the internal walls are assumed to be constructed of 12-cm-thick concrete. No furnishings except the indoor thermal sources were considered. These latter are two persons seated at two personal computers during the occupancy period (9:00 a.m. to 6:00 p.m.) and a dry process copier.

Acetone was chosen as a single pollution tracer for the study as the diffusive and sorption properties on different materials have been determined by Tiffonnet *et al.* (2002) and Blondeau *et al.* (2003). Two types of sources were considered: (1) an outdoor harmonic concentration profile showing a peak of 1.5 mg/m^3 at 3 p.m. and a minimum of 0 mg/m^3 at 3 a.m. (the contaminant is contained in the supply air); and (2) a 9-h emitting source (emission rate = 6 µg/s) representing the acetone emission from the copier during the workday period.

Applied to the reference room, the zonal model consists in a 18 sub-zone division of the room volume as illustrated in Figure 1. The plans delimiting the sub-zones cut the axes at abscissas x = 1.5 m and x = 3.5m, ordinates y = 1.5 m and y = 3.5 m and height z = 1.8 m (upper limit of the occupation zone). Regarding ventilation, three different cases have been tested: (1) mechanical ventilation (fresh air only) with a standard minimum air exchange rate of 0.7 h^{-1}; the air inlet and exhaust are located in sub-zones 0_1_0 and 2_1_1; (2) air conditioning (cooling only) with a 5 h^{-1} ventilation rate and a 0.7 h^{-1} air exchange rate during daytime (indoor temperature set point = 22.5°C), a 0.7 air exchange rate during night-time (free floating indoor temperature); the air inlet and exhaust are located in sub-zones 0_1_1 and 2_1_0; and finally (3) displacement ventilation with a 17 h^{-1} fresh air ventilation rate during daytime (22.5°C indoor temperature set point) and a 0.7 h^{-1} air exchange rate during night-time (free floating indoor temperature); in this case, the air inlets are located in sub-zones 0_0_0, 0_1_0 and 0_2_0, while the air exhaust is located in sub-zone 2_1_1. In all cases, the two occupants (with computers) are assumed to be located in sub-zones 1_0_0 and 1_2_0; the copier is assumed to be located in sub-zone 2_0_0.

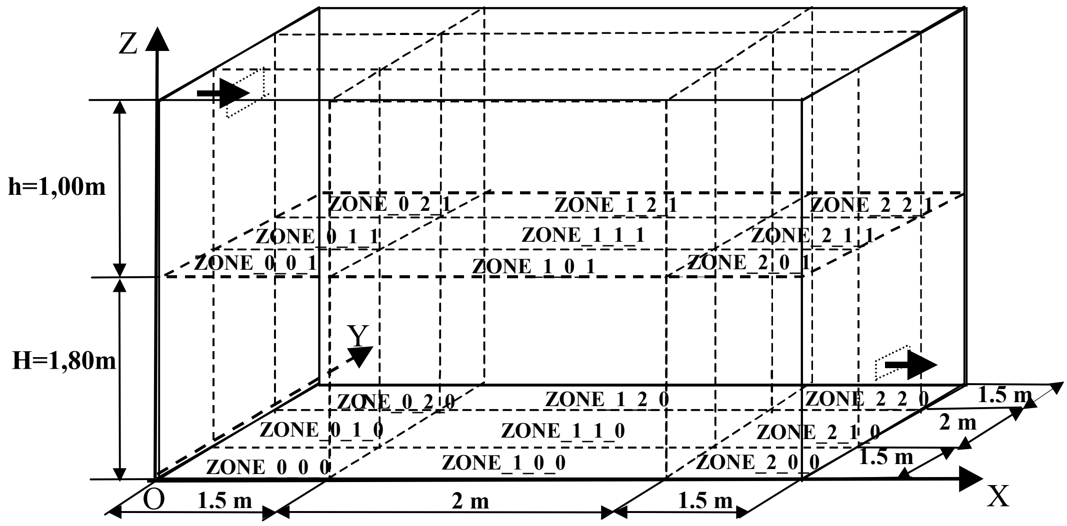


Figure 1 Division of the reference room volume for the case studies.

Whatever the case studies, the simulations were run for a simulation time corresponding to several days, until a steady periodic state was attained; the results presented below relate to this steady periodic condition. Either they correspond to the time-averaged acetone concentrations, $E_{\mathrm{loc},i}$ (mg/m^3), over the workday period in a given sub-zone i, or to the time and space averaged acetone concentrations over the same period in the nine sub-zones defining the occupation zone, E_{mean} (mg/m^3); the exposure indices are defined as follows:

$$E_{\mathrm{loc},i} = \frac{\int_{\tau=9\mathrm{h}}^{\tau=18\mathrm{h}} \rho_{\mathrm{es},i}(\tau)\,\mathrm{d}\tau}{T} \qquad i = 1,\ldots,18 \qquad (1)$$

$$E_{\mathrm{mean}} = \frac{\sum_{i=1}^{i=9} E_{\mathrm{loc},i} V}{\sum_{i=1}^{i=9} V_i} \qquad (2)$$

where $\rho_{\mathrm{es},i}(\tau)$ (mg/m^3) is the concentration in sub-zone i at time τ (h), T is the workday period (9 h) and V_i (m^3) is the volume of sub-zone i.

RESULTS AND DISCUSSION

In the frame of a previous study (Damian *et al.*, 2002), we had already demonstrated the influence of the wall and contaminant interactions on the predicted indoor air concentrations using a single zone model assuming a perfect mixing of the air. The same kind of investigation was repeated using the zonal model: the mean acetone exposure, E_{mean}, was calculated for each ventilation/air conditioning system and each acetone source, by considering or not the wall and contaminant interactions (the so-called ‘sink effect’). As Figure 2 shows, the exposure index varies a lot from one ventilation system to the other depending on the air exchange rate: when the contaminant is emitted indoors, the higher the air exchange rate, the lower the indoor pollution level. On the other hand, when the contaminant is transported from outdoors to indoors by the supply air, the higher the air exchange rate, the higher the acetone concentrations indoors. As the outdoor acetone concentration increases until 3 p.m. in the case the contaminant originates from outdoors, or acetone is emitted all the workday period long in the case the copier is the contaminant source, the exposure index is always lower when the wall and contaminant interactions are considered: the walls act as a buffer regarding indoor air pollution by accumulating acetone during daytime and restoring it during night-time. Therefore, neglecting the combined sorption and diffusion phenomena leads to an overestimation of the occupants' exposure which may be significant (up to 55%).

The heterogeneity of indoor contaminant concentrations that may result from the building ventilation is illustrated in Figure 3. It considers the case where the room is ventilated by displacement and the contaminant originates from outdoors.

First, the local exposure indices $E_{\mathrm{loc},i}$ were calculated for each sub-zone i. Then, the exposure isovalues throughout the room were determined by interpolating the data in all directions of space. Figure 3(a) presents the acetone distribution in a horizontal plan of the occupation zone (longitudinal section at height z = 0.9 m); Figure 3(b) presents these distributions in three vertical plans corresponding to cross-sections at ordinates y = 0.75 m, y = 2.5 m and y = 4.25 m.

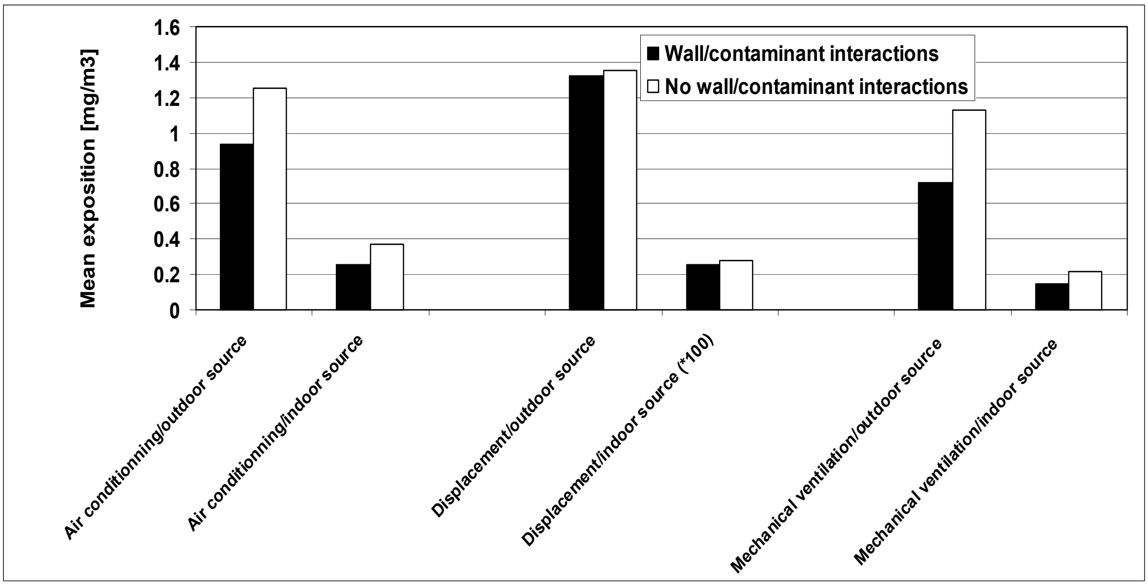
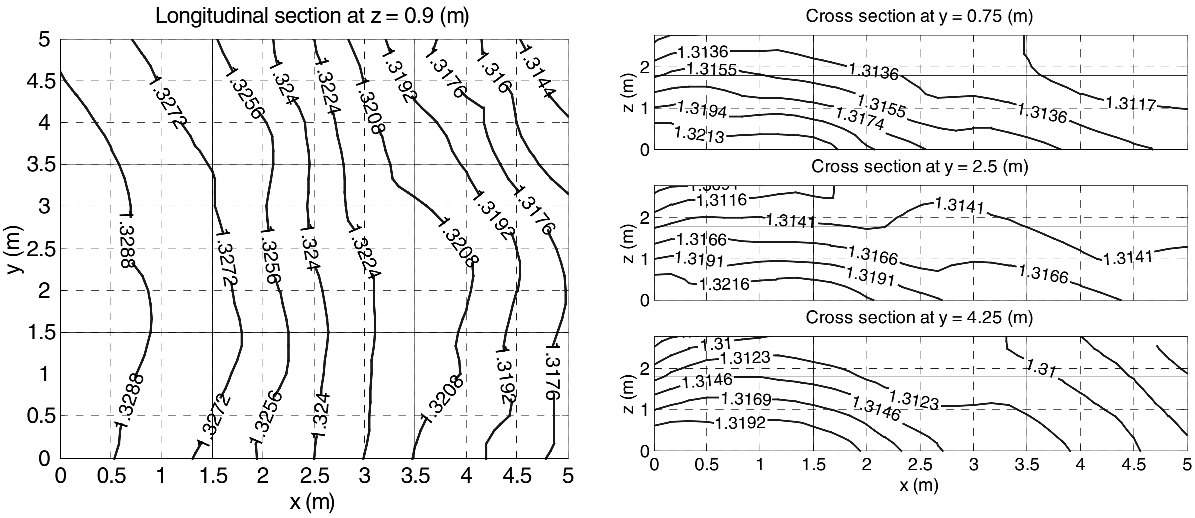


Figure 2 Comparison of mean exposure E_{mean} (mg/m^3) for the three ventilation systems considered.

Considering the location of the air inlets and exhaust, the case investigated amounts to cross-ventilation: the acetone molecules emitted indoors by the supply air move from one side of the room to the opposite side. Consequently, the concentrations are very close to one another in the occupation zone (no concentration differences greater than 2 mg/m^3 between two sub-zones). However, Figure 3(a) shows a slight concentration gradient in the main direction of the airflow (direction *Ox*). As explained above, it results from the acetone interactions with the walls: the acetone molecules transported to the pores of the wall materials are no longer transported by the airflow, thus contributing to a concentration decrease in the direction of the airflow.

In a room ventilated by displacement, the combination of low air velocities and thermal plumes generated by heat sources makes the warm air move to the ceiling, thus creating a vertical temperature gradient. When contaminants are emitted in the lower part of the room, they also rise to the ceiling and supplying fresh clean air at floor level contributes to a vertical concentration gradient and optimized ventilation effectiveness.



(a) Longitudinal section (b) Cross-sections

Figure 3 Contaminant distribution (E_{loc} in mg/m^3) in the reference room with displacement ventilation and acetone emission by the supply air.

The case investigated here is somewhat different from what is commonly assumed when designing displacement ventilation systems. Indeed, the supply air is not clean but contains acetone and there is no acetone source in the occupied spaces. As mentioned previously, in such a case, the contaminant moves through the occupation zone before entering the upper zones of the room. If no interaction with the room walls occurred, the acetone concentrations in the lower and upper zones of the room would be roughly the same, and the situation would therefore resemble that of mixing ventilation. However, due to sorption/diffusion phenomena, the vertical concentration gradient is reversed compared to what could be expected, i.e. concentrations are higher in the lower zones than in the upper zones of the room (Figure 3b). Considering the symmetry of the problem, Figure 3(b) shows similar concentration profiles in all cross-sections.

CONCLUSION

The study presented in this paper aimed at demonstrating the combined influence of materials and gaseous species interactions, on the one hand, and ventilation, on the other hand, on the distribution of contaminant concentrations inside buildings. By comparing the exposure indices calculated when the sorption/diffusion transports in wall materials are considered or not, we have first shown that these phenomena have a significant impact on air quality dynamics. The second case study presented focussed on an example where one usually expects strong heterogeneity of contaminant concentrations inside rooms and maximum ventilation efficiency. However, for the contaminant source considered, the simulations showed very slight concentration differences from one room sub-zone to another. Therefore, the results emphasize the need to consider the fact that fresh air does not necessarily mean clean air, and that the location of the contaminant sources relative to the air inlets and exhausts are of major importance when designing ventilation systems. They also underline the great interest of zonal models for such applications.

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