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A simplified analytical model of ultrafine particle concentration within an indoor environment

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Abstract. Exposure to indoor fine and ultrafine particulate matter (PM) has been recognised as a fundamental problem as most people spend over 85% of their time indoor. Experimental data derived from a field campaign conducted in a confined environment have been used to investigate the physical mechanisms governing indoor-outdoor PM exchanges in different operating conditions, e.g. natural ventilation and infiltration. An analytical model based on the mass balance of PM has been used to estimate indoor fine and ultrafine PM concentration. Indoor-outdoor concentration ratio, penetration factor and air exchange rate have been estimated and related to the differential pressure measured at the openings.
Keyword: Indoor particle concentration, Indoor/Outdoor ratio, air exchange rate, penetration factor, mass balance model.

1. Introduction

For several years now the scientific community pays attention to the problem of atmospheric particulate matter (PM) pollution, as the inhalable particles (<10 μm) are a concern to human health since they cause respiratory problems [1], [2]. Therefore, the study of PM concentration indoor, where most people spend over 85% of their time, is crucial [3]. Indoor PM pollution derives from both indoor sources and particles coming from outside. This second factor is particularly relevant in urban areas, where high outdoor PM concentrations are due mainly to vehicular traffic, wear of road surface, brakes and tires. However, an exhaustive understanding of the physical mechanisms governing such exchanges is not an easy task. Indoor pollution depends on the indoor-outdoor (I/O) PM concentration difference and on the ventilation of the considered building, which, in turn, is regulated both by the geometry of its openings and by the external meteorological conditions. A simplified analytical model could help to understand I/O pollutant flux exchanges [1], [3]. Besides, the availability of experimental data derived from field campaigns conducted in real cases is certainly of help during the calibration phase of the model.

In the present work a simplified analytical model based on the mass balance of PM is used to describe I/O particle exchanges. Field measurements carried out in a classroom of the University of Rome "La Sapienza" have been used as input data for the model. Different operating conditions have been considered during the measurement campaign to investigate both natural ventilation and infiltration.

2. Material and methods

The experimental data are derived from the field campaigns conducted in the framework of the BRiC project #22 [4]. In detail, data concerning I/O differential pressure and PM concentration were analyzed to define the relationship between the two and to highlight the role of the meteorological forcing in the I/O exchange phenomena.

2.1. Study area and instrumentation

The field campaign has been conducted within an outside a classroom located on the second floor of the "E. Fermi" building of the University of Rome "La Sapienza", Italy. The diurnal cycle of winds in Rome has a main contribution from land-sea breezes involving flows with complex pattern [5]. Figure 1 shows the layout of the room and the location of the instruments used. On the East side of the room there are nine windows (W1-W9), while two doors (D1 and D2) allow the passage to the hallway on the opposite side. The room is 3.85 m high while its floor area and total volume are 133 m^2 and 513 m^3, respectively.

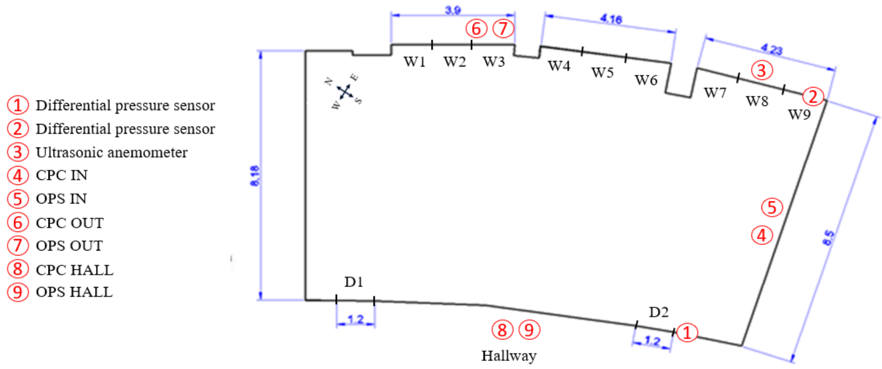

Figure 1. Layout of the classroom and location of the instruments. Measurements are in m.

PM concentration have been measured by means of two different instruments, i.e. the Condensation Particle Counter (CPC 3007 TSI) and the Optical Particle Sizer (OPS 3330 TSI). The former allows us to detect particle sizes between 0.01 μm and 1 μm, while the latter between 0.3 μm and 10 μm. In this work only CPC data acquired at 1 Hz were used for the analysis. PM concentration is given as number of particles per unit volume (#/cm^3) and was measured inside the classroom (C_{in}^M), outside the windows (C_{out}^M) and in the hallway (C_{hall}^M). Two Delta Ohm HD35ED4R1 sensors have been employed to measure the differential pressure (ΔP) between the classroom and the external environments at 1 Hz. As depicted in Fig. 1, one sensor measures I/O pressure differences at window W9 ($\Delta P_w = P_{in} - P_{out}$), while the second one measures ΔP between the hallway and the classroom at door D2 ($\Delta P_h = P_h - P_{in}$).

The field campaign consisted of three Intensive Operating Periods, hereinafter IOP#1, IOP#2 and IOP#3, conducted on 21st July 2018, 15th June 2019, and 22nd June 2019, respectively. Data were collected from 5 AM to 5 PM. During IOP#3, all the classroom openings have been kept closed, while during IOP#1 and IOP#2 window W9 and door D2 have been opened from 9:50 AM to 11:50 AM simultaneously. For IOP#2 and IOP#3 PM concentrations inside the room, outside the windows and in the hallway were available, even though the concentrations in the hallway miss for IOP#2 after 11:50 AM. On the other hand, only indoor and outdoor concentrations have been acquired on 21st July 2018.

2.2. Theoretical framework

In what follows the classroom is considered as a domain characterized by uniform PM concentration (box model), while the hallway and the outdoor are considered as external sources of particles. Moreover, only natural ventilation and infiltration are taken into account, since no artificial ventilation system was active during the experiments. Thus, the following mass balance equation can be written [1]:

$$V\frac{dC_{in}}{dt} = aPVC_F - aVC_{in} + S_0 - S_i - kVC_{in} + RL_{fl}A_{fl} \quad (1)$$

where V is the classroom volume, a the air exchange rate, P the penetration factor, C_F the forcing concentration, S_0 the internal source term and S_i the sink term. The latter is associated with particle aggregation phenomena that could cause a reduction in particle number. C_F corresponds with the outdoor concentration of PM when the air enters the room from the windows and exits through the doors, i.e. $\Delta P_w < 0$ and $\Delta P_h < 0$. Differently, C_F is equal to the hallway concentration of PM when the air circulation is reversed, i.e. $\Delta P_h > 0$ and $\Delta P_w > 0$. The first term on the left side in Eq. (1) represents the time variation of the number of particles in the box. The first term on the right represents the incoming quantity of particles per unit time from the outdoor, while the second term is the outgoing quantity of particles. The last two terms on the right side are the deposition and resuspension terms, respectively. Here, R is the particle resuspension rate, L_{fl} is the number of particles settled per unit surface, A_{fl} is the floor surface and k is the particle deposition rate.

The particle size considered in the current work is small enough to neglect deposition phenomena. Besides, given that no activity was carried out within the room during the IOPs, both the internal source and the resuspension terms can be neglected. It has also been assumed that no aggregation occurs. Thus, the mass balance equation assumes the simplified form:

$$\frac{dC_{in}}{dt} = a(PC_F - C_{in}) \quad (2)$$

The relationship between the external (C_F) and internal (C_{in}) PM concentration therefore depends only on the two parameters a and P, which model the room ventilation mechanisms. The air exchange rate a is defined as the number of exchanges of the air volume contained in the room per unit time. This parameter depends both on the geometry of the openings and on the pressure difference across them [6]. A distinction can be made between natural ventilation and infiltration conditions. The former occurs when the air flows through large openings, such as open windows and doors. The latter is defined as an unintentional air flow through very narrow openings (leakages), such as cracks in walls, wall/floor or wall/ceiling joints, windows and doors joints [7]. The penetration factor P can be defined as the fraction of particles coming from outdoor that can pass through the building envelope [3]. Indeed, in the case of infiltration some particles remain trapped into cracks due to three phenomena, i.e. i) Brownian diffusion, ii) gravitational sedimentation and iii) inertial impaction [8]. Consequently, the penetration factor depends on the pressure difference across the openings, on the particle dimension, on the geometry and the surface roughness of the cracks [3]. It is useful to mention that the ratio between the indoor PM concentration and the external one is a widely used parameter, i.e. the I/O ratio [3].

3. Results and discussion

Equation (2) allows us to model the time variations of the indoor concentration by using the forcing concentration (C_F), considered as independent variable, and varying a and P. These parameters were obtained, for the considered exchange conditions, i.e. wide openings or infiltration from leakages, partly from the experimental data and partly based on theoretical assumptions.

3.1. Penetration factor and I/O ratio

The penetration factor can be either modelled via analytical relationships describing the three processes mentioned above [7] or deduced experimentally [9]. [3], [9] and [10] reported values of P in the 0.6-1 range for particles whose dimensions were comparable to those here considered. In real cases, as the external concentration varies greatly over time, P estimation becomes rather complex.

In this work, starting from Eq. (2), P was set equal to C_{in}/C_F when $dC_{in}/\,dt = 0$ (if the air exchange rate is not zero). In detail, P was obtained by averaging the I/O ratios in the areas of the relative maximum and minimum $C_{in}(t)$. It is important to emphasize that the application of this method was possible only for IOP#3, since for the other two days no clearly identifiable extreme points were present, or the forcing concentration data was missing. The P value obtained for IOP#3 was ~0.7, which falls in the P range reported in the literature. It is worth noting that in IOP#3 the ventilation was only due to infiltrations that occurred mainly through the West side. As a consequence, P=0.7 can be assumed as the characteristic value only for the infiltration through the West side of the classroom (P_h), i.e. from the hallway. With regard to the infiltration occurring from the East side, i.e. through the leakages of the windows, a value of $P_w = 0.6$ has been set, which ensures a good agreement between measured and modelled indoor particle concentrations, as shown later. $P_h = P_w = 1$ is assumed when window W9 and door D2 are both open (natural ventilation). The inferred I/O ratio falls in the ranges 0.2-0.8, 0.2-1.5 and 0.3-1.9 for IOP#1, IOP#2 and IOP#3, respectively.

3.2. The air exchange rate

As mentioned before, a was inferred from the comparison of the measured particle concentration, C_{in}^{M} , with that calculated, C_{in}^{C}, and using the simplified analytical model (Eq. 2). Furthermore, to highlight the role played by the meteorological forcing, a has been expressed as a function of the indoor-outdoor differential pressure. In detail, C_{in}^{C} was obtained from the discretized form of Eq. (2), viz.:

$$C_{in}^{(i+1)} = C_{in}^{(i)} + a^{(i)}(P_F C_F^{(i)} - C_{in}^{(i)})\,\Delta t \tag{3}$$

where i is the iteration number, while P_F is the penetration factor estimated for each forcing, F, i.e. air coming from the windows (P_w) or from the hallway (P_h). The reason why two different values for P are needed for the present analysis was discussed in section 3.1.

The air exchange rate can be estimated as the ratio between the incoming air flow and the volume of the indoor environment. The incoming flow rate entering indoor through an opening can be expressed as a function of the differential pressure across the opening itself by means of the power law [6], [11]:

$$Q = \alpha \Delta P^{\beta} \tag{4}$$

where Q is the air flow rate and α and β are two constants. Since $a = Q/V$, it follows that:

$$a = \alpha' \Delta P^{\beta} \tag{5}$$

where $\alpha' = \alpha/V$. The ΔP values are provided by the measured differential pressure, i.e. ΔP_w when air enters the classroom from the windows or ΔP_h if air enters from the hallway.

The parameters α' and β must be calibrated for the specific case study. In particular, β is linked to the flow regime based on the drag coefficient laws [12]. It can be shown that $\beta = 1$ if the opening is very narrow (laminar flow), $\beta = 0.5$ if the opening is large (turbulent flow), while $\beta = 0.6 - 0.7$ if the flow regime is transitional or there is a variety of cracks of different nature (crack flow equation). In this work, when windows and doors were closed (i.e. infiltration condition), β was set to 0.67, as the considered classroom presents different openings whose nature is not exactly known, while $\beta = 0.5$ was assumed when natural ventilation occurred (i.e. during IOP#1 and IOP#2).

The parameter α' depends on the flow properties and on the opening geometry. Its values have been chosen to fit the modelled indoor particle concentrations, C_{in}^{C}, and the measured one, C_{in}^{M}. When doors and windows are closed (infiltration condition), two different values of α' have been estimated, i.e. one when air comes in through the windows, i.e. from the East side, and one in the case in which air passes through the opposite side. The corresponding values are $\alpha' = 2/3600$ ($s^{-1}Pa^{-\beta}$) for the East side and $\alpha' = 0.5/3600$ ($s^{-1}Pa^{-\beta}$) for the West side. Differently, when a condition of natural ventilation occurs, only one value of α' is set, i.e. $\alpha' = 15/3600$ ($s^{-1}Pa^{-\beta}$).

Figure 2 depicts the measured indoor (black line), outdoor (orange) and hallway (light blue) PM concentrations along with the modelled indoor values (red) for the three IOPs. It is important to notice that in all the three cases the PM concentration is calculated by Eq. (3) using the measured ΔP and C_F, while the parameters P, α' and β vary at every time step as described before. Firstly, we observe an overall similarity between hallway and outdoor concentrations since all the windows in the hallway were opened during the three IOPs; secondly, during the periods of natural ventilation the indoor concentration reached the external value very quickly.

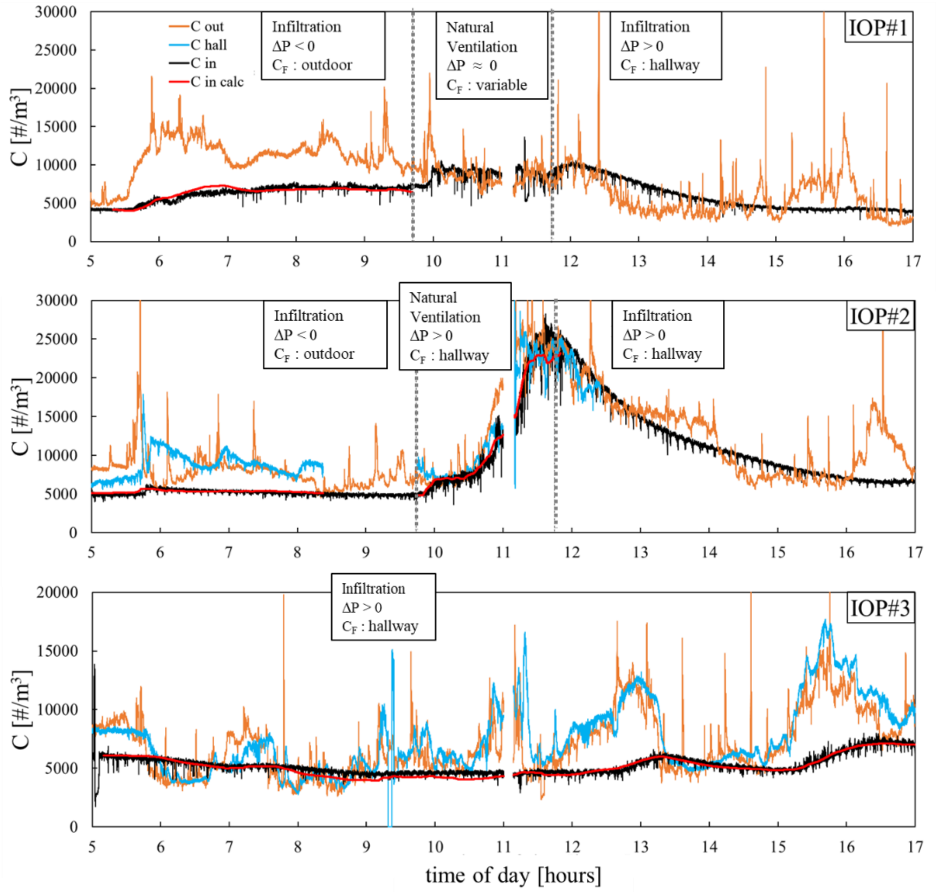

Figure 2. PM concentrations for the three IOPs measured in the classroom (black line), outside the windows (orange) and in the hallway (light blue). The red line indicates the modelled indoor concentration. The data gap at around 11:00 AM is due to instruments maintenance operations.

From 5 AM to 9:50 AM of IOP#1 (top panel), the negative ΔP indicated that it was the outdoor concentration that assumed the role of forcing in the model. The good agreement between C_{in}^{C} and C_{in}^{M} also shows that the model predicted well the indoor concentration in that period. On the other hand, during the second (9:50 AM - 11:50 AM) and the third period (11:50 AM – 5:00 PM) the ΔP sign indicated that the forcing concentration was mainly the one measured in the hallway. Unfortunately, owing to the lack of concentration measurements in the hallway during IOP#1, the application of the model in these two periods was not possible.

In the first period of IOP#2 (center panel of Fig. 2) infiltration through the windows occurred and the model reproduced well the indoor concentration. In the second period one of the doors and one of the windows were opened; the ΔP values indicated that air entered the room from the hallway (natural ventilation with hallway concentration as forcing; missing data of C_{in}^{C} are due to a gap in the forcing concentration measurements). The model worked well also for that condition ($C_{in}^{C} \approx C_{in}^{M}$). Note that the concentration peak observed both indoor and outdoor at around 12:00 is due to the presence of an external PM source, the effects of which are present almost instantaneously indoor given the condition of open window. The model is also able to simulate this situation well.

Finally, during IOP#3 (bottom panel) doors and windows were always kept closed (infiltration) and the forcing concentration was mainly the one of the hallway (positive ΔP). The results show also for this case the good agreement between measured and calculated indoor concentrations for the entire period as well as the crucial role played by the hallway concentration.

4. Conclusions

In this study a simplified analytical model based on the mass balance of PM was adopted to estimate fine and ultrafine PM concentrations within a room. Lack of activity within the room and availability of high frequency concentration data of the forcing environment are two of the main hypotheses on which the model is based. I/O ratio, air exchange rate and penetration factor were estimated from a field campaign considering both natural ventilation and infiltration. The main focus was the PM concentration and differential pressure relationship occurring between the classroom and the external environments, i.e. the outdoor and the next hallway.

The results show that the simplified model is capable of simulating the time variation of the PM concentration for all the fluid dynamic and opening conditions considered during the campaign, once the model parameters have been set based on the opening characteristics and differential pressure. The results also show that air pressure and PM concentration in the hallway play a role comparable to that of their outdoor counterpart. It is therefore essential that these assessment studies are carried out considering not only the outdoor but also the other indoor environments adjoining the room of interest.

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