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# ANALYSIS OF THE EXCHANGE OF POLLUTANT AND MOMENTUM BETWEEN OUTDOOR AND INDOOR ENVIRONMENTS. THE CASE OF A CLASSROOM IN THE FRAMEWORK OF THE VIEPI PROJECT

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**Abstract**: Evaluation of pollutant exposure and concentration peaks to which individuals are subjected in confined environments is a fundamental issue particularly in urban areas, where air pollution is due to both internal and external sources. In this work, concentration fields of indoor pollutants within a classroom of the University of Rome "La Sapienza" were numerically and experimentally investigated in the framework of the VIEPI project (Integrated Evaluation of Indoor Particulate Exposure). The field campaigns included measurements of several fluid dynamic quantities and high-frequency concentration data of fine and ultrafine particles both within the room under examination and outdoor. Furthermore, numerical simulations of flow and particulate matter concentration were carried out by means of computational fluid dynamics considering several boundary conditions. The results compare well with the experimental data collected during the field campaigns.

***Key words:*** *I/O particle concentration, indoor environment, fluid dynamics modelling, particle dispersion modelling.*

## INTRODUCTION

In the last decades, indoor air pollution has been recognised as a topic of primary importance in that population live mainly in indoor environments within which it is exposed to different kinds of pollutants. In particular, in urban areas it is necessary to monitor fine and ultrafine particulate matter as it directly affects human health. Indoor concentration peaks and exposure of these substances depend on several factors, e.g. indoor and outdoor sources, particle size distributions, ventilation and outdoor fluid dynamics (Chen and Zhao, 2011). The last two factors, in particular, are fundamental in evaluating outdoor-indoor exchanges of pollutant and momentum, both in case of large openings, i.e. windows and doors, and through leakages. Despite many studies conducted in the past concerning indoor and outdoor particle concentration, relationships between the two are not well known yet. Outdoor concentrations depend mainly by the source characteristics and building geometry (see e.g. Amicarelli et al., 2012; Leuzzi et al. 2012; Badas et al., 2017; Garau et al., 2018). The investigation of indoor particle dispersion usually presents difficulties related to the geometry. High-resolution computational fluid dynamics (CFD) modelling is a useful tool for evaluating indoor particulate matter dispersion and indoor-outdoor interaction (Blocken, 2015). Such models require detailed input data to obtain physically based results and to validate the results as well.

In this work, numerical simulations of flow and particle concentration fields within a confined real environment were carried out. Experimental data, i.e. concentrations of fine and ultrafine particles and fluid dynamic quantities collected outdoor and indoor, were used both as input data and for comparison with the numerical results.

## MATERIALS AND METHODS

The present data were collected in the framework of the VIEPI (Integrated Evaluation of Indoor Particulate Exposure) project, in which several experimental campaigns were conducted in different confined environments with the aim of evaluating the infiltration factor for particulate matter (Chen et al., 2012). Long- and short-term field campaigns were conducted during the field campaigns. In particular, three Intensive Operating Periods (IOPs) of 12 h each were conducted, where high-frequency data concerning a classroom of the University of Rome “La Sapienza” were collected. The IOPs were considered for both data analysis and numerical simulations. The building of interest is located in the centre of Rome. This district is morphologically heterogeneous, with buildings of different heights and complex geometry (Cantelli et al., 2015; Salvati et al., 2019). The diurnal cycle of winds in Rome is strongly influenced by land-sea breeze regimes for large part of the year (Leuzzi and Monti, 1997; Petenko et al., 2011), while strong convective conditions (Badas and Querzoli, 2011) usually take place during the central hours of day.

### Data

Both the long-term and the IOP campaigns included high frequency (1 Hz) measurements of indoor fluid dynamics quantities carried out by means of a 3-axial ultrasonic anemometer and two differential pressure ($\Delta$P) sensors. The $\Delta$ P sensors measure the difference in pressure between the external and internal environment. The anemometer, which is placed at the centre of the room, 2.70 m from the floor, provides the Cartesian components of the velocity field U, V and W (meridional, zonal and vertical components, respectively), pressure, temperature and relative humidity. In detail, one is located in correspondence of a window, i.e. W9, providing $\Delta P_w = P_{ind} - P_{out}$, in order to analyse the effect of the outdoor conditions, while the other is located above one of the classroom doors, i.e. D2, measuring $\Delta P_d = P_{hallw} - P_{ind}$, i.e. the difference in pressure between the hallway and the investigated room. The latter detects variations related to the opening or closing of the door itself and hence quantifies the contribution of the other indoor environments (i.e. corridors) on the considered one (Goubran et al., 2016). Moreover, outdoor wind velocity and direction were measured during the daily campaigns by means of an external ultrasonic anemometer. Furthermore, concentration in number of fine (<10 µm) and ultrafine (<1 µm) particle were measured, both outside and inside the room, using two different instruments: a condensation particle counter (CPC 3007 TSI) and an optical particle sizer (OPS 330 TSI).

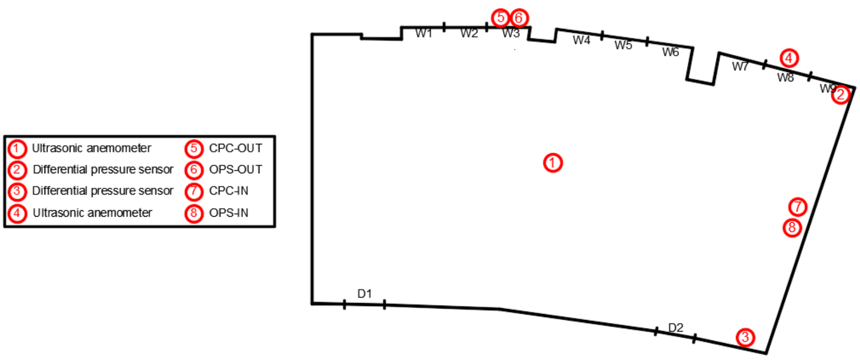


**Figure 1.** Layout of the classroom. The numbers indicate instrument positions during the IOP campaigns. D1 and D2 indicate room doors while the windows are denoted as W1-W9.

Figure 1 shows the instrument positions during the IOP. In these campaigns, different airflow conditions, i.e. natural ventilation and infiltration, and geometrical configurations, i.e. door and window openings were tested. The dataset used in this work refers to the IOP held on 21 July 2018, hereinafter referred to as IOP#1. Measurements were collected from 5:00 to 17:00. In this period, the door and the window were simultaneously opened from 9:50 to 11:50. The latter configuration, i.e. natural ventilation, was used for the numerical simulations. The whole period, i.e. from 5:00 up to 17:00, was considered to evaluate I/O exchange mechanisms.

**CFD Modelling**

The CFD software, ANSYS Fluent 18.2, was employed to simulate the airflow inside the room and evaluate particulate matter diffusion for different geometrical configurations, i.e. doors and windows openings, and boundary conditions, i.e. wind velocity and direction. The RANS equations, along with the re-normalization group (RNG) k-ε model, were employed to predict the turbulent velocity field inside the room (Xu and Wang, 2017). The simulations were carried out by using a 3D structured mesh, with a resolution of 0.075 m and consisting of about 1.200.000 nodes, reproducing the considered classroom. Besides, particle dispersion was investigated by means of the same model. Specifically, the Fluent Discrete Phase Model (DPM) was used for simulating the particle injection and indoor diffusion. The DPM is based on the Eulerian approach for the continuous phase and the Lagrangian approach for the discrete phase (ANSYS, 2011) The interaction between the two phases was taken into account by the DPM coupling the solution along with an unsteady particle tracking with a particle time step of 1 s. The injection of the particulate matter was set at the open window, considering a particle diameter of $10^{-6}$ m, the same velocity magnitude of the airflow and a mass flow rate of $5.1\times10^{-9}$ kg/s. The injection setting, which is fulfilled to represent the outdoor pollutant load, was derived by ultrafine particle concentration experimental data collected during IOP#1.

**RESULTS**

Figure 2 shows the time histories of $\Delta P_w$ (bottom panels) in conjunction with I/O particle concentrations (upper panels) to investigate the physical mechanisms governing the exchanges between the two environments. To highlight the contribution of the external conditions in the infiltration phenomena, different time intervals of the IOP#1 were considered.

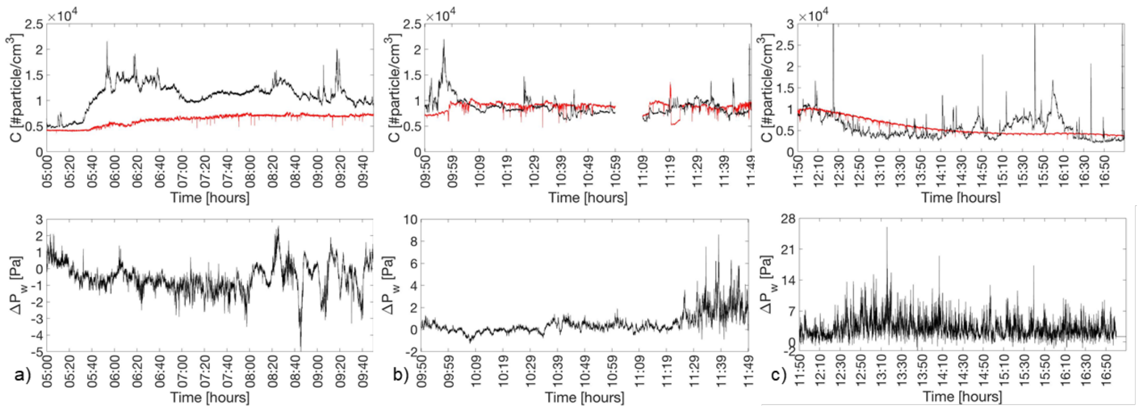


**Figure 2.** Indoor (red lines) and outdoor (black lines) particle concentration (top panels) measured at the window for different time intervals (interval-1 in panel a), interval-2 in panel b), interval-3 in panel c)) for IOP#1.

Panel a) shows the period in which windows and doors were closed (interval-1,) and the room experienced a pressure lower than outside, i.e. $\Delta P_w<0$. In this case, the indoor concentration, $C_{ind}$, tends to increase probably due to the infiltrations through the leakages of outdoor air with greater concentration. Otherwise, when doors and windows are open (interval-2, panel b) $\Delta P_w$ tends to zero and I/O particle concentrations are nearly the same after about 10 min. Finally, panel c) refers to the second period (interval-3) in which windows and doors were closed and the room experienced a greater pressure than the outside, i.e. $\Delta P_w>0$. This condition contributes to outward filtration and infiltration from the corridor, phenomena that determine the observed $C_{ind}$ decrease.

Numerical simulations of the indoor velocity field were carried out considering diverse boundary conditions. In detail, preliminary simulations were conducted in steady conditions (ST), using a 0.3 m/s inlet flow entering from the open window, normal to the boundary, and an outlet flow through the door. Different configurations (A, B and C) of the openings were considered in the simulations. The results concerning pathlines, velocity and turbulent kinetic energy fields for the three cases highlighted the great complexity of the 3D indoor field as well as its dependence on the boundary conditions. Figure 3 shows the velocity fields computed for ST-A, ST-B, ST-C.

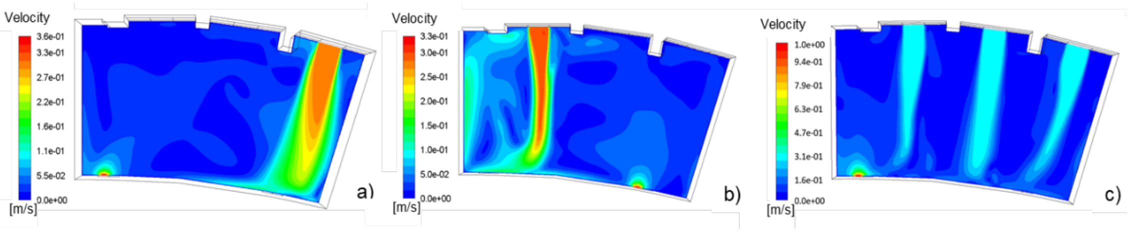


**Figure 3.** Maps of the velocity fields computed along the horizontal plane at 1.5 m above the floor for configurations A-B-C (Steady conditions).

In order to investigate the role played by the external boundary conditions in a more realistic way, unsteady fluid dynamics simulations (UNST) were carried out. In this case, experimental data concerning the outdoor velocity field, i.e. wind velocity and direction measured by the ultrasonic anemometer, were used as input data. Simulations reproducing the two hours in which the window and the door were opened during IOP#1 test, i.e. interval-2, were conducted on the same structured mesh, considering the A opening configuration and using a 15 s time step to update the inlet velocity. Figure 4 depicts maps of the indoor velocity fields calculated along the horizontal plane at 1.5 m from the floor, for the UNST-A case, at 900 s, 5400 s and 7200 s in panels a, b and c, respectively. The results show the strong flow inhomogeneity already observed for the steady cases and highlight the need to have high frequency measured data to proper set boundary conditions and hence to obtain physically-based numerical results.

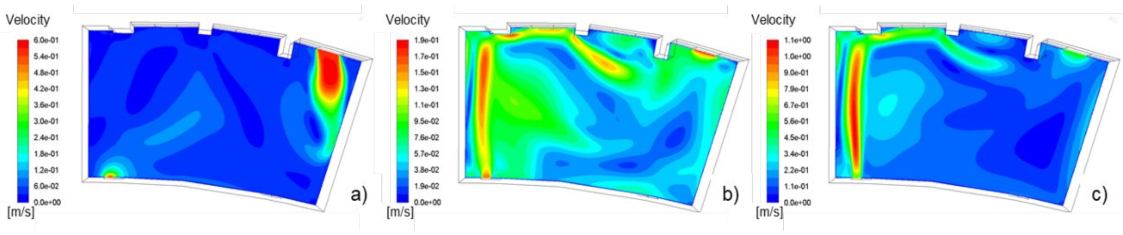


**Figure 4.** Maps of the velocity fields computed along the horizontal plane at 1.5 m above the floor in unsteady conditions (case UNST-A) at (a) 900 s, (b) 5400 s and (c) 7200 s.

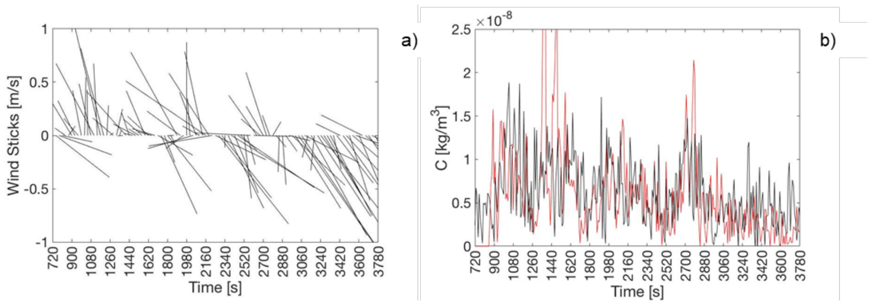


**Figure 5.** Stick plot of the external wind (a) and comparison between measured (black line) and computed (red line) indoor concentrations for IOP#1 (b).

Finally, a Lagrangian particle model based on the DPM was then coupled with the Eulerian unsteady computation UNST-A to calculate PM2.5 particle concentration fields. This simulation, hereinafter

DPM/UNST-A, refers to particulate entering the classroom from the outdoor in the 2h period of open window conditions (interval-2 in Fig. 2b). The computed concentrations were compared with those measured by the CPC (Fig. 1). Figure 5 shows computed and measured indoor particle concentrations together with the stick plot of the external wind, i.e. the inlet boundary condition at the opened window. The computed concentrations compare well with the measured ones when the airflow enters through the window, i.e. from 0 s up to 1700 s. In contrast, when the direction of the external wind rotates, i.e. from 1800s up to 4000s, there is no airflow entering the window while air enters through the door. As no injection of pollutant was set at this opening, the computed concentration decreases faster than the measured one. This fact confirms the need to model properly also airflow and pollutant concentration in the hallway.

## CONCLUSIONS

Airflow and particulate matter concentration within an indoor environment have been investigated by means of a series of field campaigns and numerical simulations. The main objective was the analysis of indoor-outdoor exchanges of mass and momentum. The results show the need to have detailed indoor-outdoor boundary conditions as well as information on flow and concentration field also in correspondence of the other indoor environments, if any, constituting the building.

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