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Computational Fluid Dynamics (CFD) Analysis Assisted by Portable Sensing Devices for Precise Assessment of Indoor Environmental Conditions

BALI N.[1], VOULTSIDIS D.[1], GIALELIS J.[1,*]

[1] Electrical and Computer Engineering Department, University of Patras, Patras, Greece
*corresponding author: Gialelis John
e-mail: jgialel@upatras.gr

Abstract Indoor air quality has become an emergent issue for human health since burdened outdoor environments, stagnant air conditions and indoor human activities (cooking, cleaning, etc.) increase the pollutant concentration. Some of the pollutants that interest the most for indoor environments are PM2.5, CO_2, CO, VOCs, and NO_2. These are measured by a wearable sensor- kit that is constructed by Applied electronics lab (APEL). Various working scenarios are set, such as human presence/absence and doing some indoor activities to measure the pollutants concentration in each case. Three kits are used and two of them are placed in the enclosed space and one close to the human body (wearable-kit). Most of the time it is noticed higher pollutant concentrations in enclosed space than those measured in atmospheric air by other local sensors. Along with the experiments, the enclosed space is computationally reconstructed and simulated for Computational Fluid Dynamic (CFD) analysis. The momentum, mass transport phenomena were coupled and solved using Ansys CFX software. The same cases were tested and compared with the experimental measurements. Conclusions such as the poor quality of indoor space under various flow conditions and at specific hours during the day have been noticed, as well as the assessment of human exposure have been performed to improve the indoor environment.

Keywords: indoor air quality, sensor wearable kit, CFD analysis, human exposure

1. Introduction

Breathing environment has become the object of many studies recently due to damaging of human health (Dockery et al., 1993). All of those confirm that the indoor air is more deadly since averagely a human spends about 87% of his/her time in enclosed spaces (Landrigan, 2017). Together with the scientific finding (in many cases) that the indoor human activities result in producing more chemical compounds that burden further the indoor environment lead to monitoring the enclosed spaces via sensors (Kumar, Singh, Arora, Singh, & Singh, 2023). Sensing technology has rapidly evolved the past years. Sensors have started to become widely used and low cost PM sensors display promising accuracy (Chen et al., 2017; Zheng et al., 2018). However, there are still some challenges and limitations associated with the usage of sensors for monitoring indoor air quality, such as challenges in terms of accuracy, standardization, sensor placement, and maintenance (hot-spot identification). In this study there is an effort to address these limitations and enhance the effectiveness and reliability by combining the measurements with CFD analysis.The CFD analysis can provide valuable insights into the airflow patterns, ventilation effectiveness, and dispersion of pollutants within enclosed spaces, but emphasizing in qualitative analysis (Sørensen & Nielsen, 2003). By incorporating CFD information into the analysis, the accuracy of sensor measurements can be enhanced. CFD simulations can help understand how pollutants disperse and interact with the surrounding environment, allowing for better interpretation of pollutants transported indoors. Beyond that, CFD is used for identification of High Exposure Areas: by integrating sensor measurements with CFD analysis, it becomes possible to identify areas within indoor spaces where human exposure to pollutants is likely to be higher [5]. CFD simulations can help pinpoint locations with elevated pollutant concentrations, such as near emission sources, in poorly ventilated areas or where air is stagnant. This knowledge can inform targeted interventions to reduce exposure risks in these specific areas.

In the present study a sensor kit is developed and used for measurements of indoor air pollutants (CO_2, CO, VOCs, NO_2 and PM2.5), which are combined with an advanced numerical CFD model under specified working scenarios (Table 1) to give insight of the enclosed environment pollution state and human exposure level at different locations. All these data are examined to understand pollutants pattern for indoor spaces, as well as to store the outcomes in a database for further exploitation (Digital Twin database) and enforce the expandability of the results to other cases.

Table 1. Working scenarios

Action	Outcome
1. Window closed and human absence	Air pollution minimum level
2.Sligthly open window (20%) and human absence	Air pollution level without human
3.Widely open window case (80%) and human absence	Indoor air pollution is compared with outdoor measurement
4.All the above cases are tested when human is present	Human contrbution to indoor environment

2. Materials and Methods

2.1. Experimental setup

An air quality kit was built around the sensor equipped with an ESP8266 microprocessor that continuously collected and uploaded data to an online database. The PM2.5 sensor used in this study was the PMS5003. The sensor is capable of measuring PM1, PM2.5 and PM10 and its accuracy has been extensively highlighted in the existing literature. Data were collected for a period of 30 days at a sampling rate of 15 seconds. The collected data was pre-processed to remove outliers and erroneous measurements. Statistical analysis was performed using Python to calculate descriptive statistics and identify trends in the data.

2.1. Theoretical model

A numerical model is developed for obtaining the distribution of pollutants in an enclosed space, room-scale anslysis, see Figure 1. Momentum and mass transport Reynolds Averaged Navier-Stokes (RANS) equations are solved using ANSYS CFX software. The model is considered in laminar regime and as isothermal, due to almost stable room temperature (22^0C) during the experiments. A background pollution level is applied for CO_2= 400 ppm, which is the average value of the daily minimum (between 9am to 12pm) and for thirty days of collected measurements.

For laminar air flow is described by the following set of equations 1.<u>Continuity Equation</u>, 2.<u>NS Momentum transport</u>, 3.<u>Pollutants transport</u> :

$$1.\ \frac{\partial \rho_{air}}{\partial t} + \nabla\left(\rho_{air}\underline{u}\right) = 0$$

$$2.\ \rho_{air}\frac{\partial \underline{u}}{\partial t} + \rho_{air}\left(\underline{u}\nabla\right)\underline{u} = \nabla\left[-p\underline{I} + \mu\left(\nabla\underline{u} + \left(\nabla\underline{u}\right)^{T}\right) - \frac{2}{3}\mu\left(\nabla\underline{u}\right)\underline{I}\right]$$

$$3.\ \frac{\partial c_i}{\partial t} - \nabla D_{i\_air}\nabla c_i + \overline{u}\cdot\nabla c_i = Q_i$$

where, ρ_{air} and μ_{air} are the air density and viscosity, u is the velocity field c_i is the i-species concentration, D_{i_air} is the diffusion coefficient of species i in the air inside the enclosed space, Q_i is the pollution source term which is defined by calibration of the model and the experimental measurements.

In Figure 1, there are sensors, whose values are implemented as a dirichlet boundary condition in the simulation domain (known values). For the window an inlet type boundary is applied (velocity of air is $u=10^{-4}$ [m/s]) while the other walls are no-slip. Reynolds number is estimated and the changes in this dimensionless number is presented in 3.3. The space is discretized by 1 million triangular mesh elements. The solution time is from 2 to 5 minutes.

3. Results and Discussion

3.1. Indoor air pollution level for PM2.5 in an enclosed space

Various pollutants are measured inside the encolused space, however particular focus is placed on PM2.5 concentration, which is very crucial for human well-being. In Figure 2 the PM2.5 dynamic concentration is shown from 9am to 12pm of a typical day where the window was widely opened (working scenario 3). The measurements come from the inside stable sensor, since it is the case of human absence. The results show that the PM2.5 concentration is high earlier in the morning as it is outside (PurpleAir), due to school and go-to work traffic. It gradually decreases but it is averagelly remains close to 52 $\mu g/m^3$ during the whole day. The interesting result is that the higher PM2.5 concentration is achieved during the night between 10 pm and 5am. This result is observed during a three month period (Pikridas, Tasoglou, Florou, & Pandis, 2013).

3.2. Distribution of air pollutant at various Re (Reynolds) number

Different flow conditions have been applied for capturing the difference in CO_2 concentration distributions inside an enclosed space Figure 3. The higher Re number means higher velocity of air inlet, this consequently leads to more pollutants concentration versus unit of time. This is the reason of higher cocnetration of CO_2 at the higher Re number. Another interesting outcome is when Re equals to 40, the concentration is more homogeneously distributed around the space, without practically having isolated reagion (where air is stagnant). However for Re equal to 400 this lead to a huge isolated area (~1m radius) pointed in right hand side scheme with a dashed black line, where the pollutants remains there, so if human is inside this area there is a high possibility of inheal air of highly concetrated pollutants that exist there. Another interesting result is the lower air condition performs better towards well-ventilated environment.

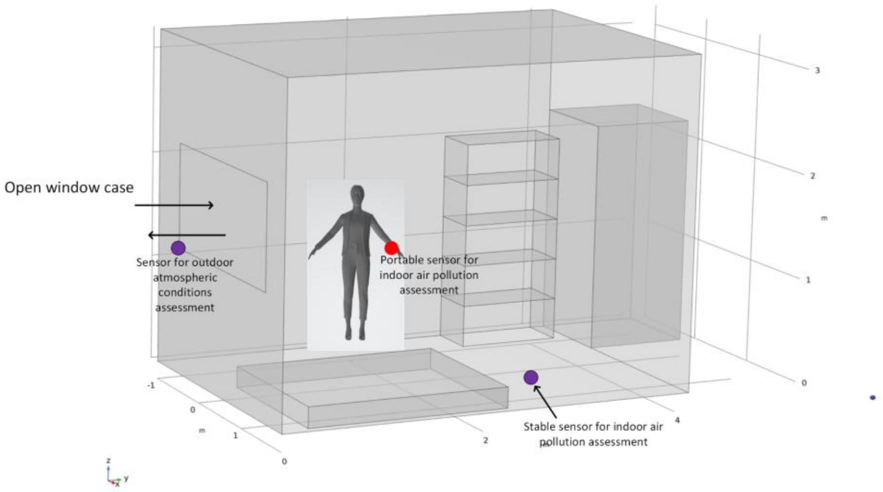

Figure 1. Enclosed space where experiments performed and simulation domain

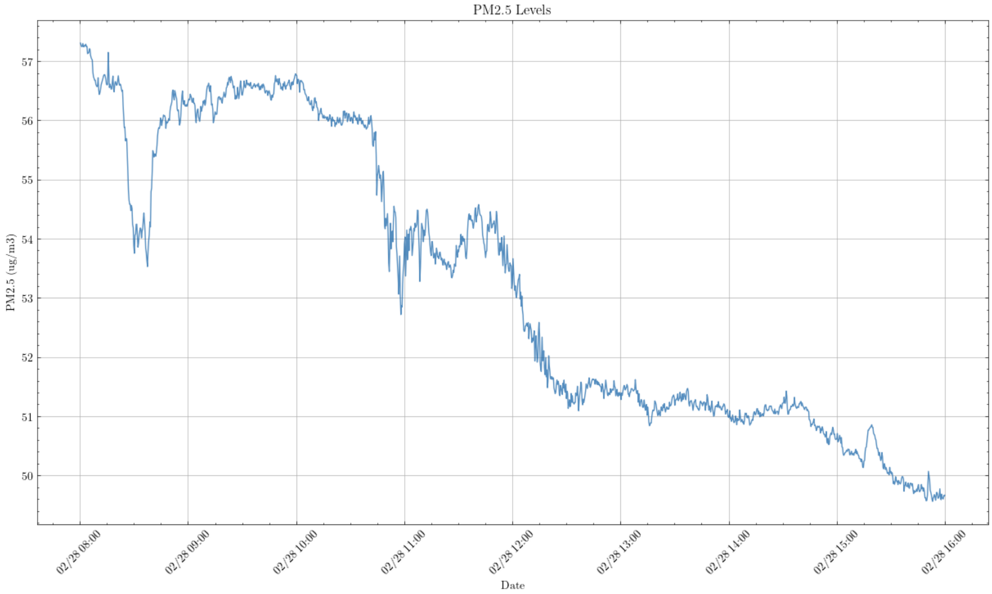

Figure 2. PM2.5 concetration during a period from 8am to 4pm.

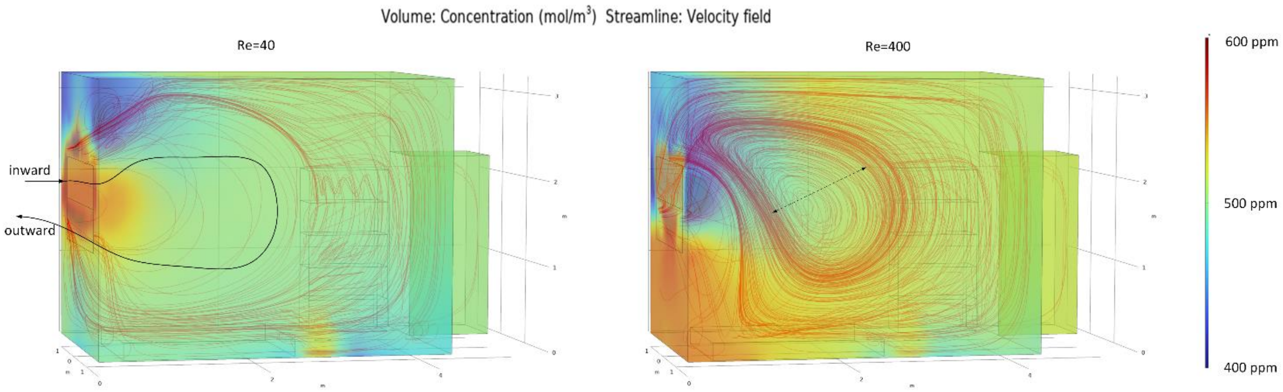

Figure 3. Volume rendering of CO_2 distribution and depiction of flow field with red streamlines at different inlet air velocities

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