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EXTENDED ABSTRACT

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Laboratory-scale modeling of air circulation and pollutant dispersion in a real indoor environment

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Abstract:

In the framework of the VIEPI (Integrated Evaluation of Indoor Particulate Exposure) Project, air circulation and pollutant dispersion within an amphitheatre-shaped university classroom were investigated by means of a laboratory-scale model and compared with field measurements. A 1:20 scale model of the real classroom was placed in a hydraulic circuit, allowing controlled inflow and outflow of water to mimic natural, isothermal, steady-state ventilation. The indoor velocity fields were reconstructed using feature tracking techniques, while pollutant dispersion was analysed through white-light excited fluorescence using fluorescein as a passive tracer. Scale-model velocity results provided detailed insights into the three-dimensional circulation and were in quite accordance with the ones obtained from 3D-axis ultrasonic anemometer measurements realized in the real classroom. The time-history concentration values, as well as the filling and emptying times, of the indoor environment under consideration were estimated, highlighting fundamental aspects for assessing indoor air quality and exposure risk in complex, crowded environments.

INTRODUCTION

Indoor air quality has become a subject of growing concern due to the large amount of time people spend in confined environments such as homes, offices, schools, and classrooms. In such spaces, individuals may be exposed to a wide spectrum of airborne pollutants, often with highly variable concentrations, potentially leading to adverse health effects.

Despite the increasing scientific interest, as demonstrated by the growing number of studies [1-8] and the diverse methodologies employed — field measurement campaigns, laboratory experiments and numerical simulations — the characterization of pollutant concentrations in indoor environments remains an open challenge. This is due to the complex interplay of multiple driving factors. Indoor pollutant dispersion is strongly governed by airflow patterns established within the space, which, in turn, are influenced by several interdependent variables: external flow conditions, indoor–outdoor exchanges, thermal stratification, room geometry and the location and nature of emission sources (whether internal or external). The inherent difficulty in isolating these factors in real-world contexts explains the usefulness of modeling to improve understanding of indoor pollution dynamics.

In the present work, air circulation and pollutant dispersion within a real indoor environment are investigated through laboratory-scale modeling. The selected case study, a university classroom (Aula V. Giacomini, Sapienza University of Rome) with an amphitheatre geometry, represents a particularly relevant example due to its complex geometry and high occupancy levels. The analyses were carried out within the framework of the VIEPI Project (Integrated Evaluation of Indoor Particulate Exposure), whose primary objective was the assessment of indoor air quality [1]. Within this project, the chosen classroom was the focus of an integrated study combining field measurements with both experimental and numerical simulations.

Airflow fields were characterized using the Feature Tracking technique, while pollutant dispersion was evaluated through concentration time histories as well as filling/emptying phase analysis. The simulated results were then compared with in-situ measurements to validate the experimental approach.

MATERIALS AND METHODS

Experimental setup

Experiments were conducted in the Hydraulics Laboratory of Sapienza University using a 1:20 scale model ($65 \times 56.5 \times 27.5$ cm) of the Aula V. Giacomini classroom (Fig. 1). The model was integrated into a hydraulic circuit with water as working fluid. Desks and teacher's desk were reproduced by 3D printing, while walls and ceiling were made of 1-cm plexiglass to allow optical access. Two doors (8×5 cm) behind the teacher's desk were connected to 100-cm plexiglass channels of equal cross-section to ensure stable inflow and outflow, reproducing natural ventilation. The circuit, operating in either open or closed loop, included a pump, tanks, regulating valves, and a flowmeter. Tests were carried out under steady inlet flow (3300 l/h), with constant inlet water temperature to simulate isothermal conditions. The Reynolds number at the inlet jet was ~21,000, ensuring dynamic similarity. The experimental setup was equipped with a feature-tracking system, consisting of a high-speed camera (1024×1280 px, 250 fps) and a white-halogen lamp (~0.02 m light sheet) for velocity field measurements. The acquisition system included dedicated software for reconstructing particle trajectories—i.e., impurities in the water passively transported by the fluid—from a Lagrangian perspective.
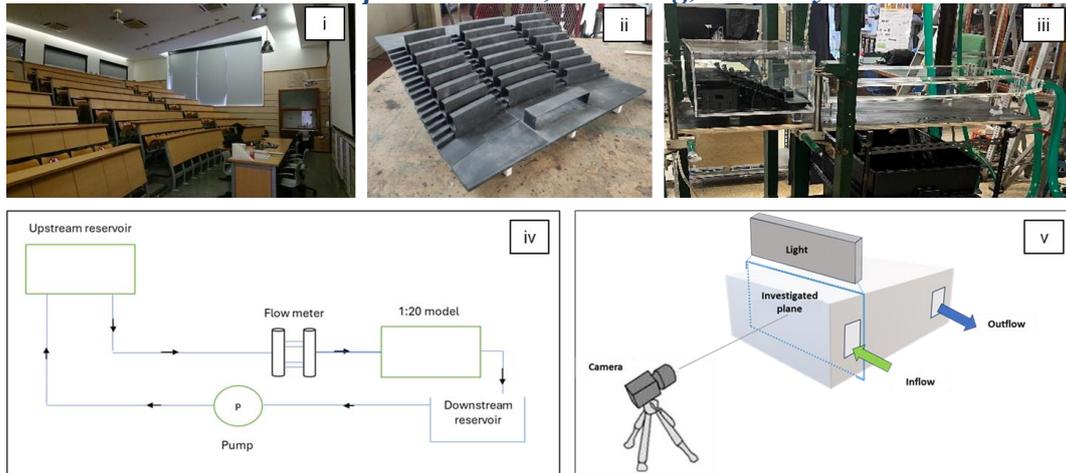
Figure 1 – Photographic images of the classroom, the 1:20 model and the experimental apparatus in panels (i), (ii) and (iii) respectively. In panels (iv) and (v) simplified schematic representation of the experimental apparatus and the image acquisition system.

From these trajectories, instantaneous and time-averaged velocity components were derived on regular grids, adopting an Eulerian framework. Ten horizontal and vertical planes were analysed to obtain a three-dimensional velocity field. Images were acquired at 250 fps for 120 s per plane. Pollutant dispersion was investigated using fluorescein as a passive tracer, continuously injected upstream of the inlet channel to simulate an outdoor pollutant entering the classroom. Images were acquired at 250 fps on the vertical mid-planes of both inflow and outflow doors. Concentration fields were obtained by correlating grayscale pixel intensity with fluorescein concentration. Concentration time series were derived during the filling, complete mixing, and emptying phases.

Field measurements

In the real classroom, airflow velocity and particulate concentrations were measured under controlled, steady-state, and isothermal ventilation conditions. Ventilation was imposed by placing eight fans 2 m in front of the door opening, using a dedicated inlet corridor. A continuous outdoor particle source was generated by burning incense sticks upstream of the fans. Air velocity was measured with a network of triaxial sonic anemometers (10 Hz sampling frequency) installed at nine locations within the classroom at different vertical heights. Concurrently, nine optical particle counters, positioned on the benches at equivalent locations, measured particle concentrations at a frequency of 1 Hz for different size classes.

RESULTS AND DISCUSSION

Mean velocity fields, variance, and turbulent kinetic energy were derived from images on ten planes. Figure 2 shows mean streamlines on vertical planes A–E. The inlet jet (~20 cm/s on plane A) remains horizontal, then aligns with the rows of desks, weakening along its path. Near the last bench, the velocity decreases by one order of magnitude, and the jet detaches, forming counter-rotating vortices in the gallery. These propagate longitudinally, enlarging and stabilizing, as seen on planes B and C. A large

counterclockwise vortex appears on plane C, rising from the desks to the ceiling and descending near the teacher's desk.
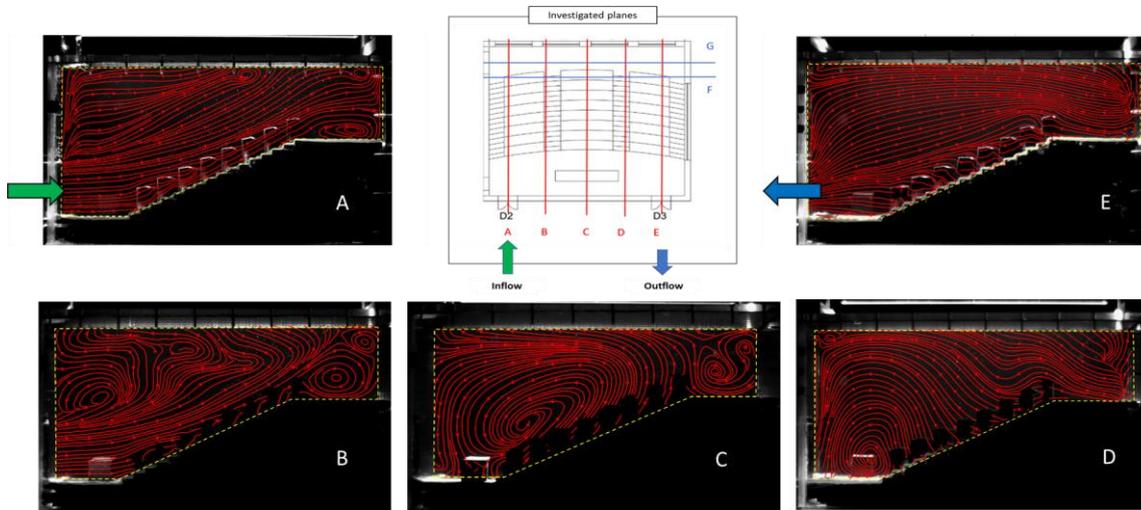

Figure 2 – Streamlines of the mean velocity field on planes A–E. In the upper central panel, diagram of the realised image acquisition planes.

On the outlet plane (E), streamlines remain parallel, with no gallery recirculation. Velocities are low (~1.5 cm/s) across the plane, increasing only near the exit. These results highlight the strong influence of room geometry, particularly the amphitheatre layout and the arrangement of desks, in shaping the velocity field and driving the formation of secondary circulation structures.

Velocity fields from the scale model were compared with in-situ measurements (Fig. 3). Vector plots at the anemometer positions show good agreement between datasets, confirming the reliability of the experimental modeling.
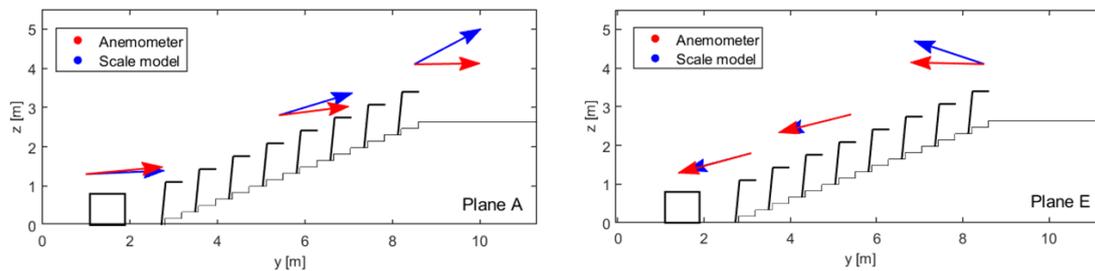

Figure 3 – Vector plots of the velocity fields from scale model (blue) and in-situ data (red).

Pollutant dispersion

Figure 4 shows concentration time histories during the filling and emptying phases, measured on the mid-planes of the inlet and outlet sections where particle counters were installed. Values were normalized by the maximum observed during complete mixing and plotted over time. The curves highlight similar overall dynamics during both phases, with differences mainly associated with vertical position. At the first bench, the pollutant arrives earliest and rapidly reaches its asymptotic value. Conversely, the higher positions (4° and 8° bench) are reached later and display a noticeably slower growth in
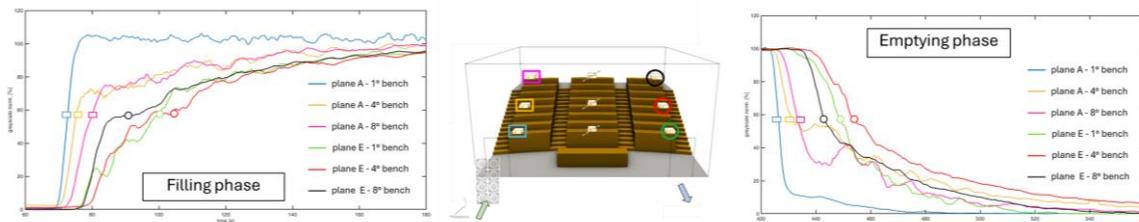
Figure 4 – Concentration time histories at the particle counter locations during the filling and emptying phases.

concentration. A comparable pattern is observed during the emptying phase: lower positions close to the inlet clear first with a steep decline, while higher locations exhibit a delayed and more gradual decrease. On the outlet plane, the decay is consistently slower across all heights.

CONCLUSIONS

The analysis of the flow field revealed a complex circulation strongly influenced by the classroom geometry, with several stable vortical structures observed on different planes and apparently disconnected from one another. The comparison with field data not only allowed the validation of the experimental model but also confirmed the value of this methodology for reconstructing the three-dimensional flow field, which in-situ anemometric measurements can describe only locally. The observation of such a complex circulation, together with the different concentration time histories, suggests the need to further investigate pollutant dispersion in real and geometrically complex environments, in order to identify potential accumulation zones associated with increased concentration levels and exposure risks. These critical aspects could be further exacerbated in the presence of thermal stratification, a highly plausible condition in real classrooms and one that will be specifically addressed in future studies.

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