23rd International Conference on
Harmonisation within Atmospheric Dispersion Modelling
for Regulatory Purposes
15-19 September 2025, Hamburg, Germany

EXTENDED ABSTRACT

Numerical investigation of natural ventilation and stratification in an amphitheatre classroom

Pier Giuseppe LEDDA

DICAAR, University of Cagliari, 09123 Cagliari, Italy

piergiuseppe.ledda@unica.it

Maria Grazia BADAS

DICAAR, University of Cagliari, 09123 Cagliari, Italy

Giovanni LEUZZI

DICEA, Sapienza University, 00184 Rome, Italy

Paolo MONTI

DICEA, Sapienza University, 00184 Rome, Italy

Armando PELLICCIONI

Italian Workers' Compensation Authority (INAIL), 00078 Rome, Italy

Agnese PINI

DICEA, Sapienza University, 00184 Rome, Italy

Alessandro SEONI

DICAAR, University of Cagliari, 09123 Cagliari, Italy

Giorgio QUERZOLI

DICAAR, University of Cagliari, 09123 Cagliari, Italy

Abstract

Indoor air pollution is a major health risk, yet research on natural ventilation in workplaces and classrooms of large height remains limited. We numerically study the airflow and temperature fields in a model of a real amphitheatre classroom to assess ventilation, dispersion, and thermal comfort under stratification. The classroom exchanges heat through walls, occupants, and ventilation doors. Results show inflow velocity as the primary driver: low velocities allow occupant heat fluxes to dominate and cause poor air quality as well as discomfort in upper tiers, while higher velocities promote mixing, reduce stratification and improve comfort. External temperature further modulates airflow, with colder air limiting penetration and warmer air enhancing mixing from the bottom. These findings advance understanding of buoyancy-driven ventilation in large, stratified indoor spaces.

Introduction

The effectiveness of indoor environments in ensuring health and comfort largely depends on air quality and thermal conditions. Poor indoor air quality (IAQ) is recognized as a serious health risk, involving particulate matter and volatile organic compounds, which may cause respiratory irritation, eye discomfort, and contribute to disease transmission. Interest in IAQ has grown significantly in recent decades since ventilation, heating, and air conditioning account for nearly half of building energy use. Human occupancy makes the assessment of IAQ a problem of fundamental interest for harmonization of practices since heat fluxes, movement, exhalation, and particle release interact with the surrounding environment and generate buoyancy-driven convection and stratification. Such thermal gradients, often exceeding 1°C per meter, create barriers to ventilation unless broken by sustained airflow, though excessive velocities may cause draught discomfort to occupants. The competition between buoyancy and advective transport therefore determines both IAQ and comfort. Due to the complex geometries, multiphysics interactions, and long occupation times of real classrooms, CFD has become a reliable tool for analysis. RANS models are especially popular since they balance computational cost and accuracy. Achieving effective ventilation in classrooms and lecture halls is particularly challenging because of high occupancy, long exposure times, and the likelihood of stratification from occupant thermal plumes. Prior studies often focused on flat-floor geometries, while amphitheatre classrooms remain less explored. In this work, we analyze the mean turbulent airflow in a typical university amphitheatre classroom, crowded by students and with fresh air coming from one of the doors located at the ground floor level on the wall behind the teacher's desk (fig. 1) and exiting from a second door, symmetric on the same wall, based on the "Giacomini" classroom at the Sapienza University of Rome, where a series of analyses were conducted as part of the "Integrated Evaluation of Indoor Particulate Exposure" (VIEPI) project to analyze the role played by micrometeorology and indoor airflow in determining indoor particle matter concentration.

Methods

We compute the steady turbulent flow with thermal buoyancy in the amphitheatre classroom reported in fig. 1 (L = 13.0 m, D = 11.3 m, H = 5.5 m). The two external doors (1.3 × 2.0 m) act as inlet and outlet: fresh air enters through the right door, with uniform velocity U and external temperature T_e, and exits through the left door. A reference indoor temperature $T_0 = 20$ °C is imposed. Internal walls (lateral, ground, ceiling) exchange heat with an adjacent indoor environment at T_0, while the front wall exchanges with T_e using a heat transfer coefficient of *1.6 W/(m²K)*. Desks, stairs, and upper ground walls are treated as adiabatic. Each occupant is modeled as a constant heat source (111 W), representative of sedentary activity. The emitted heat is divided into convective (45%) and radiative (55%) components; the latter is redistributed as a constant wall flux. This setup ensures coupling between inflow, occupant loads, wall conduction, and external temperature conditions. Numerical simulations are carried out with the OpenFOAM®

solver *buoyantBoussinesqSimpleFoam,* which employs the Boussinesq approximation to describe thermal buoyancy. Air quality is assessed through the Age of Air framework, i.e., by solving a steady advection–diffusion equation with turbulent diffusivity (Sc_t = 0.7). Zero age is imposed at the inlet and zero-gradient conditions elsewhere.

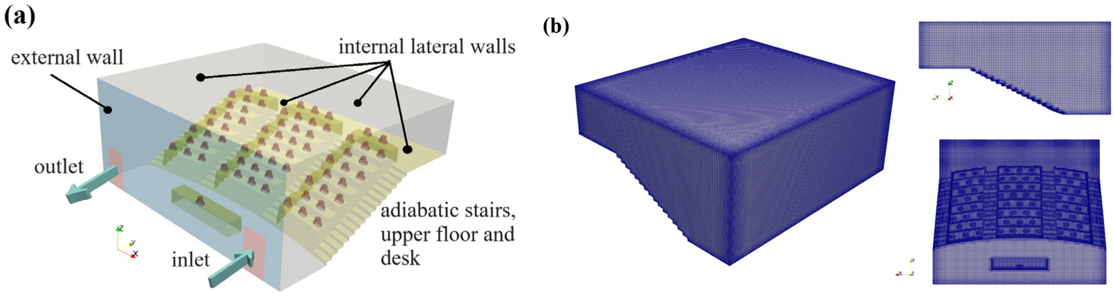

Fig.1 (a) Sketch of the configuration and (b) mesh employed in the simulations.

Results: reference case

In the following, we assume ideal, but still realistic, conditions for the inlet and outlet ventilation to perform systematic analyses. We initially consider a reference condition with an inlet mean velocity U = 1.0 m/s and an external air temperature, T_e, equal to the indoor building temperature T_0 = T_e = 20 °C. Second, we investigate the effect of a decreasing (U = 0.5 m/s) and increasing (U = 1.25 m/s) inlet air speed while keeping the external temperature constant (T_e). Finally, we explore different external temperature conditions by increasing (T_e = 30°C) and decreasing (T_e = 10°C) the temperature while keeping the inlet velocity to its reference value, U = 1.0 m/s.

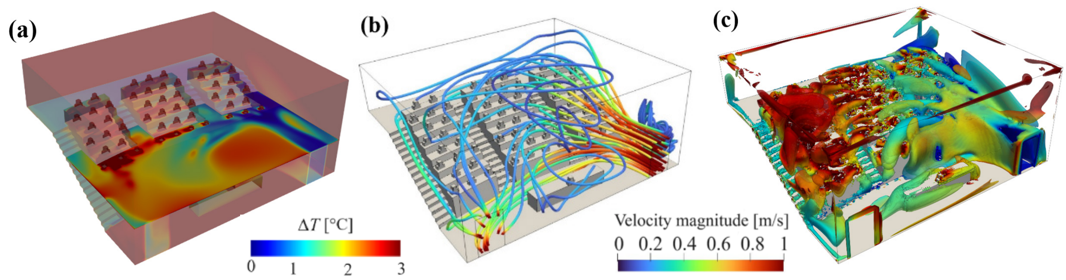

Fig. 2 Flow in the reference case: (a) colormaps of $\Delta T = T - T_e$ at a height of 3 m, (b) streamlines colored with velocity magnitude, (c) iso-surfaces of the Q-criterion colored with $\Delta T = T - T_e$.

In the reference case (U = 1.0 m/s, T_e = T_0 = 20 °C, fig. 2), the temperature field shows colder regions aligned with the inlet jet, the latter deviating toward the room centre and expanding with height, while higher temperatures accumulate near the ceiling and in the front area above the inlet. Specifically, thermal plumes rise above occupants, competing with the inlet jet, which bifurcates into a strong lower branch sweeping along the ground and a weaker upper branch rising along the right wall before descending on the left. Streamlines reveal two main recirculation regions: a small coherent vortex near the inlet and a large one above the teacher's desk spanning the room height. Vortical structures confirm the interplay between momentum-driven jets and buoyancy-driven convection, with colder, horizontal features dominating the lower right side and warmer, vertical structures prevailing in the upper left. Overall, the flow field is shaped by the balance between inlet momentum and occupant heat fluxes, with effectiveness depending on jet penetration within the room and external temperature.

Effect of the inlet flow rate and external temperature

At low inlet velocity ($U = 0.5$ m/s, $T_e = T_0$), the jet lacks momentum to break stratification, remaining confined to a narrow stream near the floor and directly short-circuiting inlet and outlet (fig. 3a). Above the first desk row, temperature deviation exceeds 3 °C, producing a sharp transition between a cooler, well-ventilated lower zone and a warmer, strongly stratified upper zone. In this configuration, the flow above the desks is dominated by occupant plumes. By contrast, at higher inlet velocity ($U = 1.25$ m/s), momentum dominates buoyancy: most of the incoming air spreads across the tiers and along the right wall, reducing stratification and yielding a more uniform vertical temperature field (fig. 3b). Small buoyant plumes persist mainly in the upper-left zone where the jet influence is weak. Elsewhere, high velocities suppress coherent plumes.

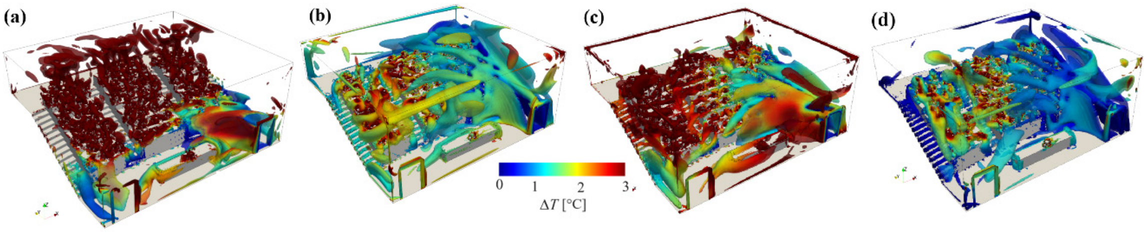

Fig. 3 Iso-surfaces of Q-criterion colored with $\Delta T = T - T_e$. (a,b) Effect of the inlet flow rate with $T_e = T_0$: (a) $U = 0.5$ m/s, (b) $U = 1.25$ m/s. (c,d) Effect of external temperature with U=1 m/s: (c) $T_e = 10$ °C, (d) $T_e = 30$ °C.

The effect of external temperature is assessed by lowering and raising T_e by 10 °C relative to T_0 while keeping $U = 1$ m/s. For $T_e = 10$ °C, the colder inflow remains confined to the lower-front part of the amphitheatre, forming a strong stream-tube directly linking inlet and outlet (fig. 3c). This produces pronounced stratification, with a slow recirculation near the ceiling and two distinct regions: the lower-right zone dominated by inlet momentum and the upper-left zone dominated by occupant plumes**.** Conversely, for $T_e = 30$ °C, the warmer inflow propagates upward, enhancing mixing and breaking stratification (fig. 3d).

Results: comfort and air quality

Thermal comfort was evaluated using percentage of people dissatisfied (PPD) according to ASHRAE Standard 55, i.e., the fraction of occupants likely to feel thermally uncomfortable. We report horizontally averaged values (fig.4a-b). At low inlet velocity ($U = 0.5$ m/s), the strong stratification produces a steep vertical temperature gradient: upper tiers are significantly warmer ($\Delta T > 3$ °C), resulting in high PPD. Increasing inlet velocity ($U = 1.0$–1.25 m/s) reduces stratification, yielding more uniform vertical temperatures and lower PPD values, with only minor cool discomfort near the jet. Horizontally averaged profiles confirm that PPD rises with height at low flow but remains nearly constant at higher velocities. Eventually, we present in fig.4c the age of air, which measures the time required for fresh air to reach a location, and thus ventilation effectiveness. Horizontally averaged age of air rises with height, with upper amphitheatre tiers experiencing the highest values under low inlet velocity or cold inflow. Higher velocity or warmer air reduces stratification, with lower age of air.

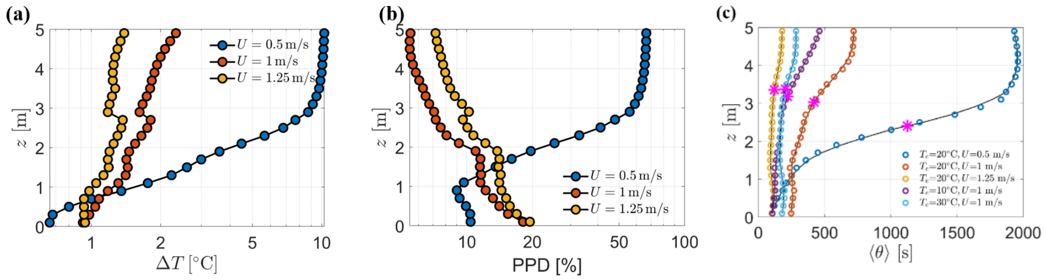

Fig. 4 Thermal comfort for T_e = 20 °C and different inlet velocities. Horizontal average of the temperature defect ΔT (a) and PPD (b) as functions of the height. Blue circles indicate the case U = 0.5 m/s, red circles indicate U = 1.0 m/s, and yellow circles indicate U = 1.25 m/s. (c) Horizontally averaged values of the age of air, θ, as a function of the height. Magenta stars indicate the average in the whole volume.

Conclusion

In amphitheatre classrooms, occupant comfort and air quality are controlled by the interplay between inlet air velocity and thermal stratification. Low inlet velocities allow buoyant plumes from occupants to dominate the upper tiers, producing vertical temperature gradients, large Age of Air, and increased discomfort. Conversely, higher inlet velocities promote mixing throughout the room, reducing thermal stratification, lowering the Age of Air, and enhancing overall thermal comfort. The sloping amphitheatre geometry amplifies stratification effects observed in flat rooms, making the upper tiers particularly sensitive to ventilation performance. Temperature deviations closely follow the Age of Air distribution, suggesting that simple temperature monitoring can serve as a practical proxy for assessing ventilation efficiency and guiding the design of effective airflow strategies in classrooms of significant height, within a harmonization perspective across fluid mechanics and health and comfort assessment.

Acknowledgments

This study was partially supported by the Italian workers' compensation authority, Istituto Nazionale Assicurazione e Infortuni sul Lavoro (INAIL) within the Research Activity Plan 2019-2021.