

Analysis of CO₂ Dispersion in Air-Conditioned Office Spaces with Varying Occupancy Configurations

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Indoor air quality (IAQ) plays a critical role in occupant health and productivity, with carbon dioxide (CO₂) concentration serving as a key indicator of ventilation performance. This study applies computational fluid dynamics (CFD) to analyze CO₂ transport and airflow behavior in office environments with varying configurations. The CFD model builds on previously validated work: airflow matched to anemometer data, mesh independence confirmed, and CO₂ field validated against sensor measurements. It is adapted for office conditions. Two office spaces are modeled, both featuring distinct air conditioning (AC) systems: window-type unit (Site I) and ceiling-mounted 4-way cassette unit (Site II). Airflow validation produced root mean square errors (RMSE) of 0.185 m/s and 0.27 m/s for Site I and Site II, respectively. At $t = 2$ h and maximum occupancy, Site I recorded 2,121 to 2,137 ppm at breathing height with a homogeneous distribution. In contrast, Site II recorded 1,930 to 2,620 ppm, demonstrating strong spatial localization and less effective mixing. Although the ceiling-mounted 4-way AC regulated temperature effectively, it concentrated CO₂ in specific quadrants, reducing ventilation efficiency. Occupant distribution, particularly in meeting room settings, further influenced pollutant buildup, demonstrating the role of occupancy patterns in indoor pollutant distribution. These findings underscore the importance of HVAC design: careful planning of AC placement, airflow paths, and room layout is essential to ensure uniform air distribution and prevent stagnant CO₂ zones.

1. Introduction

Indoor air quality (IAQ) is an important factor in maintaining human health and comfort, especially for spaces where people spend long periods of time working, at leisure, or otherwise occupying the location, as they can be exposed to various pollutants. These are the main concerns of IAQ, and are often undetectable to human senses, being invisible, tasteless, and odorless. Poor IAQ and pollutant buildup may lead to various health issues, such as lethargy, dizziness, irritation, and other conditions which fall under the term Sick Building Syndrome (SBS), or to diagnosable illnesses which are directly caused by pollutants, called Building Related Illnesses (US EPA, 2015). These are of particular concern in office spaces, where people work for extended periods and productivity can suffer as a result of these health issues. Proper ventilation is key to preventing buildup of pollutants. Evaluating the performance of ventilation systems becomes an important step in determining the IAQ of a given space. Carbon dioxide (CO₂) is a commonly used indicator for IAQ since it has predictable emission patterns and can indicate the efficiency of ventilation systems. It is a relatively stable gas and buildup can cause discomfort and drowsiness. Computational Fluid Dynamics (CFD) can be used to model the airflow for an indoor space. By using models of pollutant transport, it can also simulate the flow of CO₂ and predict concentrations within a room.

Previous CFD-based studies have highlighted the importance of mapping CO₂ dispersion in relation to occupancy and HVAC configuration. Mou et al. (2022) analyzed CO₂ concentrations in a seminar room and emphasized the influence of occupant count and location on sensor placement. Hoang et al. (2025) demonstrated how CFD can guide HVAC refinement by considering occupancy-driven emissions and AC system type. Mazlan et al. (2024) investigated the effect of AC relocation on CO₂ distribution but excluded occupants from the simulation, limiting the applicability of findings to real-world scenarios. These studies

underscore the need to examine how actual occupant distributions interact with different AC configurations to affect indoor pollutant buildup.

This study aims to map CO₂ concentrations in rooms with varying configurations of air conditioning (AC) systems and occupancy patterns, specifically in office settings. The goal is to characterize the flow patterns that result from different kinds of AC systems, and how buildup of CO₂ is affected across the space when different numbers of people stay in different locations.

2. Methodology

Two sites are used in this study, referred to as Site I and Site II, shown in Figure 1. They are offices of different sizes, occupancy, and ventilation setups. The sites emulate typical day-to-day office conditions. Site I is 30.6 m² with a single window-type air conditioning unit. The office has two doors, one leading outside, and the other to an adjoining room. Up to 5 people work in this office at a time. Site II is 29.1 m² with a ceiling-mounted 4-way cassette-type (multi-directional supply) air conditioning unit. It is typically only occupied by 1 to 2 people but may have up to 20 during events such as meetings. It has a single door leading to an adjoining indoor room.

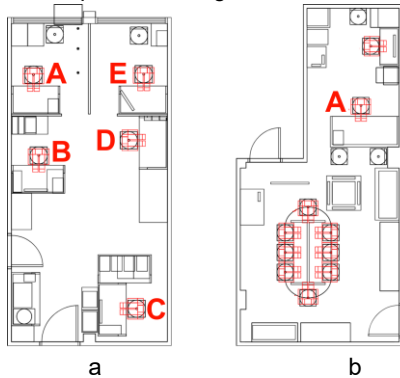


Figure 1: Diagrams of (a) Site I and (b) Site II

2.1 Model Framework and Validation Approach

A hot-wire anemometer measured airflow near the ventilation supply outlets at 1 m, 1.5 m, and 2 m distances to define the CFD inlet conditions. The model builds on prior validation from Estaquio et al. (2024), which used time-dependent simulations in a controlled indoor setting to match simulated airflow with anemometer data, confirm mesh independence, and reproduce CO₂ concentration patterns from a sleeping occupant source. The current work adapts this framework to office environments with distinct AC configurations. Since the occupant is active during working hours, the exhaled CO₂ concentration is increased from 3.6 % to 4.0 % (ASTM, 2012). Validation in the present study focuses on airflow, which is the dominant driver of how CO₂ builds up and spreads in space.

2.2 Site Occupancy Variations

Different configurations of occupants are considered for each site. This allows for insight into how different conditions resulting from some being used for meetings as well as day-to-day work activities, or where hybrid work setups are in place and occupants have varying schedules. Three configurations are considered for Site I. Configuration 1 is for when all tables are occupied, representing the full in-person operating capacity of the office. Configurations 2 and 3 only have one occupant for work hours during hybrid setups. Two configurations are considered for Site II. Configuration 1 represents typical work hours with one office table occupied. Configuration 2 represents the other use of the office space as a meeting room, where up to 8 people occupy the large table at the other end of the office.

3. Results

3.1 Site I Configuration 1 (5-person setup)

The velocity contour at the mid-plane of the AC inlet, taken from the XY plane, is illustrated in Figure 2. Here and in the next figures, X-, Y-, and Z-axes denote streamwise, spanwise, and vertical directions, respectively. The airflow dynamics follow a direct trajectory, with the high-velocity jet extending across the entire length of the room before gradually dispersing to the sides. Due to the momentum of the incoming air, it effectively circulates through the space before returning to the AC inlet, completing a continuous recirculation loop. This

pattern establishes the primary ventilation behavior within the confined space, which significantly influences pollutant dispersion and CO₂ accumulation zones. The first configuration, which includes five occupants, served as the basis for airflow simulation validation, yielding a root mean square error (RMSE) of 0.185 m/s. Since the human cuboid models do not significantly obstruct airflow, particularly in the direct path to the AC inlet, their presence does not alter the overall ventilation dynamics.

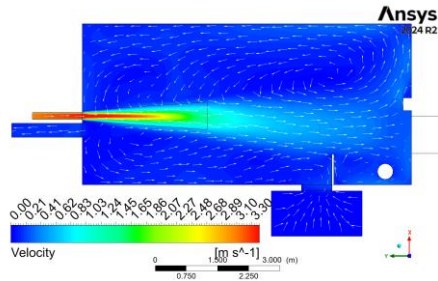


Figure 2: Site I Velocity Contour at AC Inlet Mid ($Z=1.905$ m)

All CO₂ concentration contours are extracted at $t=2$ h from the start of CO₂ production. This first slice, taken along the mid-plane of the AC inlet in the YZ plane, provides insight into vertical stratification of CO₂ distribution, as shown in Figure 3a. As observed, some degree of stratification is present, but the overall concentration remains relatively uniform across the plane, as indicated by the range (2,100–2,140 ppm). Additionally, the contour confirms that the AC is effectively recirculating air, with CO₂ levels in the recirculated flow closely matching those in the room. This validates the correct implementation of the UDF for CO₂ recirculation.

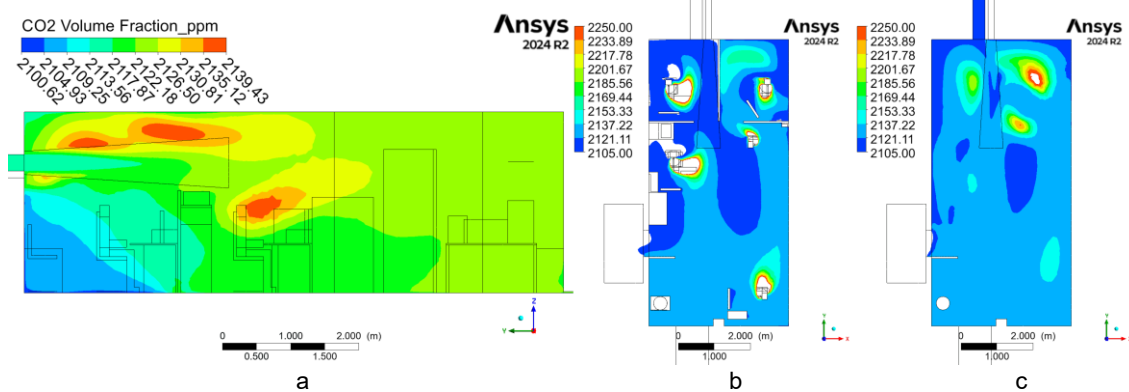


Figure 3: Site I Config. 1 – CO₂ Concentration Contours at (a) AC inlet mid ($X=1.651$ m), (b) sitting height, $Z=1.195$ m, and (c) standing height, $Z=1.75$ m

Figures 3b and 3c show XY-plane slices analyzed at 1.2 m (sitting height) and 1.75 m (standing height), respectively. These slices provide insight into horizontal CO₂ distribution at occupant breathing levels. It is evident that the room maintains a relatively homogenized CO₂ concentration, with values ranging between 2121–2137 ppm dominating most of the contour plots. This suggests that the airflow pattern in this configuration promotes even mixing, minimizing significant concentration gradients within the occupied space. In Figure 3b, the effect of partitions on CO₂ diffusion can be observed, although the impact appears minimal. The partitions create localized airflow variations, slightly influencing how CO₂ disperses within the room.

While the average CO₂ concentration exceeds the recommended 1,200 ppm threshold, this spatial mapping highlights how airflow-induced distribution patterns contribute to pollutant buildup. These insights are essential for guiding CFD-based ventilation redesign.

3.2 Site I Configuration 2 (single occupant only, closest to AC unit setup)

In this configuration, the analysis primarily focuses on Occupant A, who is positioned closest to the AC unit. Due to the high velocity of the AC supply, the exhaled CO₂ is carried away from the area directly above the AC, resulting in the lowest CO₂ concentration recorded within this contour range, as displayed in Figure 4a. However, despite this effect, the overall CO₂ concentration variation remains minimal, with values ranging between 772–786 ppm. The distribution shows that Occupant E's seat records the lowest CO₂ concentration, likely due to being positioned at the end of the recirculation cycle and the presence of a partition, which influences local

airflow patterns, as shown in Figures 4b and 4c. These results further emphasize how air circulation and obstacles within the room shape pollutant dispersion, highlighting areas of lower exposure to exhaled CO₂ due to airflow-driven dilution.

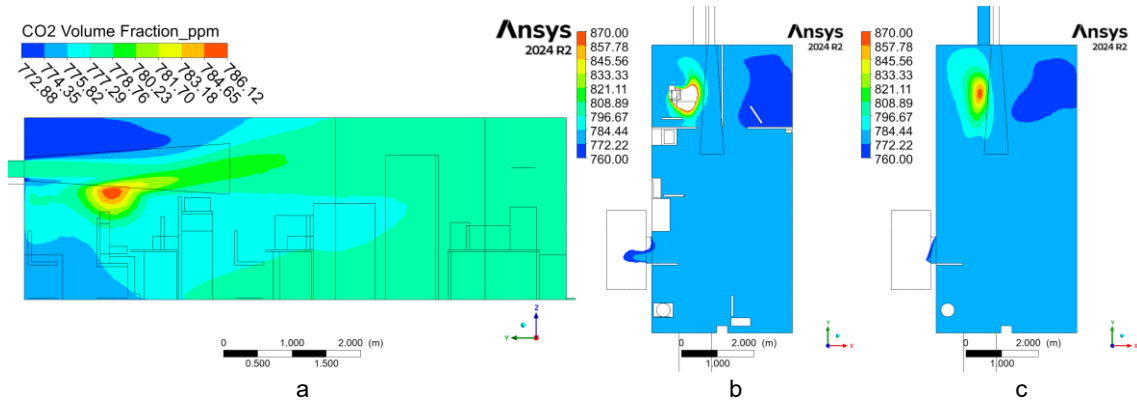


Figure 4: Site I Config. 2 – CO₂ Concentration Contours at (a) AC inlet mid ($X=1.651$ m), (b) sitting height, $Z=1.195$ m, and (c) standing height, $Z=1.75$ m

3.3 Site I Configuration 3 (single occupant only, furthest from AC unit setup)

In this configuration, only Occupant C cuboid model is introduced, positioned farthest from the AC inlet. Due to the lower airflow velocity near this source, vertical stratification is once again observed, as shown in Figure 5a. As expected, the high-velocity airflow from the AC, combined with the influence of partitions, helps dilute and redistribute CO₂ in other parts of the room. This effect is particularly noticeable in the vacant position of Occupant A, where lower concentrations are maintained.

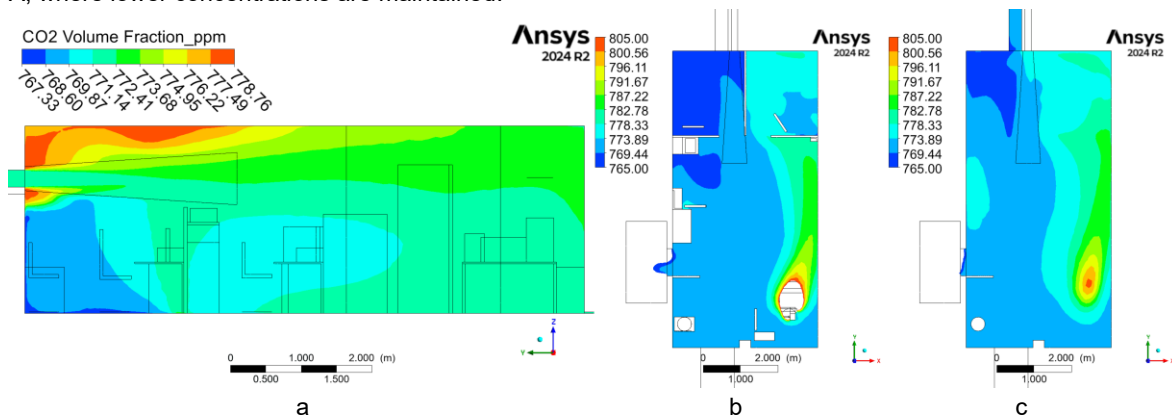


Figure 5: Site I Config. 3 – CO₂ Concentration Contours at (a) AC inlet mid ($X=1.651$ m), (b) sitting height, $Z=1.195$ m, and (c) standing height, $Z=1.75$ m

Referring to Figure 2, it is evident that these recirculation patterns significantly impact CO₂ transport and dispersion. The airflow from the AC unit drives horizontal movement of air, creating circulation loops that redistribute exhaled CO₂. This effect is particularly noticeable in the high-concentration regions near the occupants' mouths, where the air movement determines the extent of CO₂ buildup before it mixes into the surrounding airflow. At sitting height in Figure 5b, the CO₂ plume extends outward but remains relatively contained within the breathing zone. At standing height in Figure 5c, CO₂ tends to disperse more horizontally due to air dynamics, with a more elongated concentration pattern forming before dilution occurs. These findings reinforce the importance of ventilation effectiveness at different occupant heights, suggesting that airflow adjustments may be necessary to prevent localized CO₂ accumulation in occupied zones.

3.4 Site II Configuration 1 (single-occupant setup)

The velocity contours at the mid-plane of the AC inlets are shown in Figure 6. To facilitate discussion, the inlets are defined based on their airflow direction. In Figure 6a, the left inlet is referred to as the North (N) inlet, while the right is the South (S) inlet. In the Figure 6b, the left inlet is referred to as the East (E) inlet, while the right is

the West (W) inlet. During the experiment, the vanes sat at a 30-degree angle from the top wall, a configuration replicated in the CFD simulation as depicted. It is particularly interesting to analyze how four high-velocity air streams influence CO₂ transport. From the velocity vectors overlaid on the contours, several recirculation zones can be identified within the room. These airflow loops will be further examined in the CO₂ concentration contours to assess their impact on pollutant dispersion and accumulation patterns. The maximum velocity of this AC unit (1.88 m/s) is significantly lower than that of Site I's AC (3.3 m/s), an aspect that can be analyzed as well. Velocity validation gives an RMSE of 0.27 m/s, likely due to mismatch between the actual vane angle and the assumed 30° in the simulation. The model still captured the dominant airflow structure and recirculation behavior.

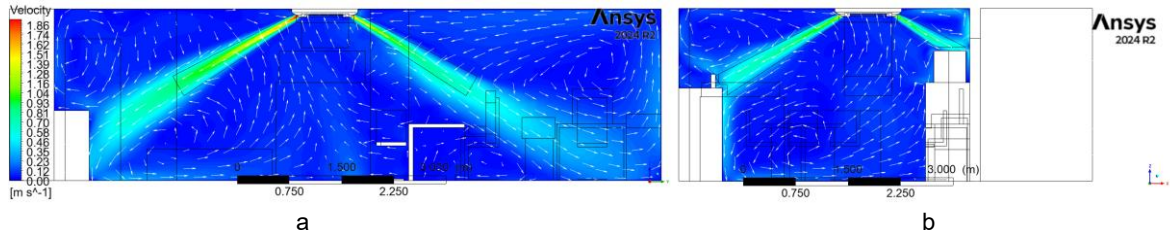


Figure 6: Site II Velocity Contours at AC inlet mid: (a) $X=2.707$ m and (b) $Y=3.89$ m

The Site II Configuration 1 includes only Occupant A, who spends most of the time in the room. Figure 7a and 7b present the CO₂ concentration contours at the same planes as those in Figure 6, allowing a direct comparison between velocity and pollutant distribution. A noticeable disparity in CO₂ concentration is observed between the regions influenced by the E/W inlets. The high CO₂ concentration on the north side of the room suggests that recirculated air from the N inlet plays a role in redistributing exhaled CO₂, despite being partially obstructed by the E and W inlets as well as the AC outlet. This recirculation effect helps maintain a relatively uniform CO₂ distribution, preventing extreme localized accumulation and ensuring that pollutant dispersion remains consistent throughout the room.

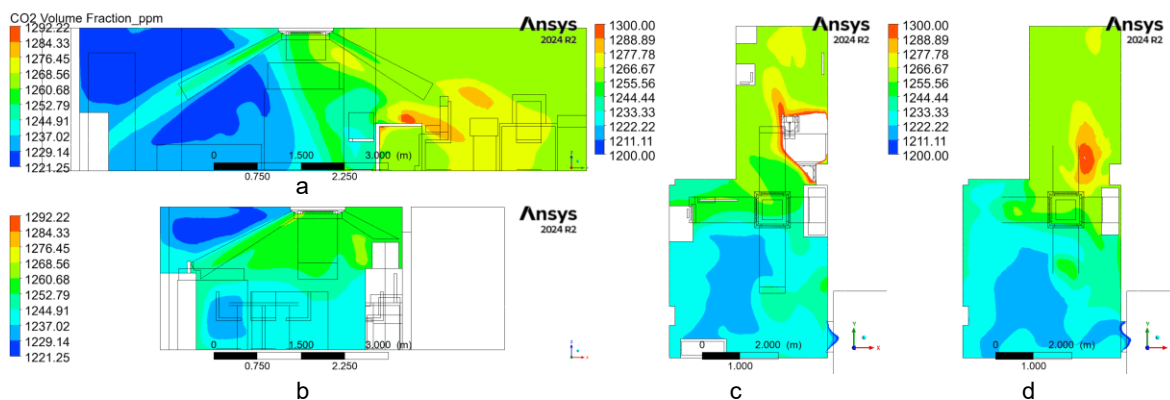


Figure 7: Site II Config. 1 – CO₂ Concentration Contours at AC inlet mid, (a) $X=2.707$ m and (b) $Y=3.89$ m, and at (c) sitting height, $Z=1.195$ m, and (d) standing height, $Z=1.75$ m

The effect of obstruction on CO₂ recirculation becomes more evident when examining the CO₂ concentration contours in the XY plane at sitting (1.2 m) and standing (1.75 m) heights, as shown in Figure 7c and 7d, respectively. These contours illustrate how airflow barriers, such as ventilation inlet configurations, influence pollutant dispersion within the room. This results in localized accumulation zones, while the rest of the space remains relatively well-mixed due to overall ventilation effects. Nonetheless, with a CO₂ concentration range of 1200–1300 ppm, the overall CO₂ levels in the room appear to be moderately well-mixed, indicating that while localized accumulation exists, the ventilation system still facilitates reasonable air exchange. The relatively narrow concentration range suggests that stagnant zones are minimal, and CO₂ is generally dispersed throughout the space without extreme pockets of high concentration.

3.5 Site II Configuration 2 (8-person meeting setup)

In this configuration, an 8-attendee meeting setup is considered. The workstations from Configuration 2 are vacated, and all occupants are seated around the meeting table. This redistribution of occupants alters airflow and CO₂ transport, as seen in Figure 8.

Notably, the North side of the room exhibits a higher CO₂ concentration than the S side, which aligns with expectations given the placement of attendees. This further validates the hypothesis that the E and W AC inlets, along with the AC outlet, obstruct direct airflow exchange, creating localized CO₂ accumulation zones. The top-view CO₂ concentration contours, Figures 8c and 8d, illustrate how the North inlet also influences pollutant distribution. Similar to the effect observed with the E and W inlets, the N inlet contributes to trapping high CO₂ concentrations, particularly compressing them within the NE quadrant of the room.

This observation raises a critical question regarding the suitability of a ceiling-mounted 4-way AC unit for a room of this size. While this AC type enhances thermal comfort by providing multi-directional ventilation, its airflow pattern evidently affects CO₂ transport by limiting dispersion and encouraging localized accumulation zones.

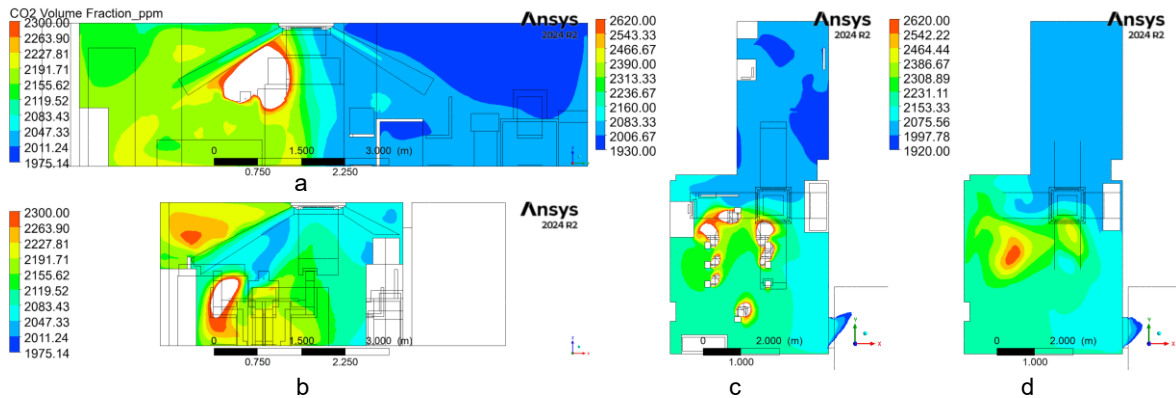


Figure 8: Site II Config. 2 – CO₂ Concentration Contours at AC inlet mid, (a) $X=2.707$ m and (b) $Y=3.89$ m, and at (c) sitting height, $Z=1.195$ m, and (d) standing height, $Z=1.75$ m

4. Conclusion

This study applied a validated CFD model to assess CO₂ transport in two office spaces with distinct AC systems and occupancy setups. Results showed that airflow from AC units, particularly their direction and intensity, directly influenced CO₂ movement and accumulation. The window-type AC produced more uniform dispersion, while the ceiling-mounted 4-way cassette AC led to stratification and quadrant-specific buildup due to obstructed recirculation. Occupant distribution further shaped these patterns, confirming that both ventilation design and room use affect pollutant behavior. These findings support the need to evaluate HVAC setups not just for thermal comfort but also for pollutant dispersion, especially in dynamic occupancy conditions. While both sites recorded CO₂ levels exceeding the 1,200-ppm threshold, CFD-based spatial analysis offers guidance for redesigning ventilation strategies to meet indoor air quality standards.

Acknowledgements

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