Validation of CFD Simulations for Natural Ventilation in Hospital Wards Using CO_2 Decay Method*

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Abstract— **This study validates computational fluid dynamics (CFD) simulations of natural ventilation in hospital wards using the CO_2 tracer gas decay method, in accordance with ISO 16000-8. Field measurements were conducted in a single-patient room at the Picardy Wallonia Medical Center (PWMC) and compared with CFD results from DesignBuilder and OpenFOAM. Results showed strong agreement, with differences within 10%, confirming the reliability of CFD models in predicting ventilation performance. This study demonstrates the potential of natural ventilation to enhance indoor air quality and thermal comfort in healthcare environments.**

I. INTRODUCTION

Indoor air quality (IAQ) in healthcare facilities is a critical factor influencing patient safety, staff well-being, and infection control. Poor IAQ can result in discomfort, decreased productivity, and an increased risk of both short- and long-term health complications [12–14]. In hospital environments, where occupants are highly sensitive to airborne contaminants, effective ventilation strategies are essential for maintaining a healthy indoor environment and reducing the transmission of airborne pathogens.

A widely used indicator for assessing ventilation performance and IAQ is the local mean age of air (AoA), which represents the average time taken for air to travel from an inlet to a specific location in a room [5–7,15]. A lower AoA generally signifies better ventilation efficiency, as stale air is replaced with fresh air more rapidly. The ISO 16000-8 standard provides a robust methodology for determining AoA experimentally using a tracer gas decay technique, ensuring consistency and reliability in measurements [1].

Several studies have explored ventilation performance in different building types using both experimental and numerical approaches [2–4,8–11]. Sandberg [5] and Sandberg and Sjöberg [6] introduced methods for evaluating ventilation effectiveness using statistical approaches, while Li et al. [7] extended the concept through the introduction of total air age. Computational fluid dynamics (CFD) has become an important tool for predicting airflow patterns, thermal comfort, and air quality in indoor spaces. Previous research has applied CFD to diverse environments, including computer rooms [2], food processing facilities [3], and naturally ventilated offices [4]. However, the application of CFD validation in hospital wards remains limited, despite the critical importance of ventilation in these settings for infection control and energy efficiency. Recent studies emphasize that effective ventilation design, particularly through natural ventilation strategies, can significantly reduce airborne disease transmission and improve thermal comfort, making it a vital consideration for healthcare environments [12–14].

The tracer gas decay method, recommended by ISO 16000-8, remains one of the most practical techniques for evaluating ventilation effectiveness and has been successfully used in both experimental investigations and CFD validation [8–11]. Van Buggenhout et al. [15] demonstrated the feasibility of using data-driven modeling to determine AoA in ventilated spaces, highlighting the potential for integrating experimental and simulation-based approaches.

This study addresses the current research gap by validating CFD simulations of natural ventilation in a hospital ward using the CO_2 tracer gas decay method, following ISO 16000-8 guidelines. The experimental work was conducted in a single-patient room at the Picardy Wallonia Medical Center (PWMC) in Tournai, Belgium. CFD models were initially developed using DesignBuilder for preliminary analysis and then refined using OpenFOAM for detailed simulations. The objectives of this research are to:

(1) validate CFD predictions with real-world measurements,

(2) quantify AoA under different natural ventilation scenarios, and

(3) assess the reliability of CFD models as decision-support tools for improving IAQ and natural ventilation design in healthcare facilities.

By integrating experimental data with advanced CFD modeling, this study provides a validated framework for designing energy-efficient and health-oriented ventilation strategies, contributing to infection control and overall indoor environmental quality in hospitals.

II. PRESENTATION OF CASE STUDY

The Picardy Wallonia Medical Center (PWMC) in Tournai, Belgium, features a seven-story extension (73,000 m², 601 beds) designed with operable windows to enable natural ventilation. Two ward types exist: single-bed rooms for privacy and infection control, and multi-bed wards with innovative layouts maximizing bed spacing. Multi-bed wards, located on building wings, benefit from natural airflow and offer multiple window configurations, enabling varied ventilation strategies. These characteristics, combined with

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patient window-opening behavior during summer, make PWMC an ideal setting for validating CFD simulations of thermal comfort and IAQ under natural ventilation scenarios.

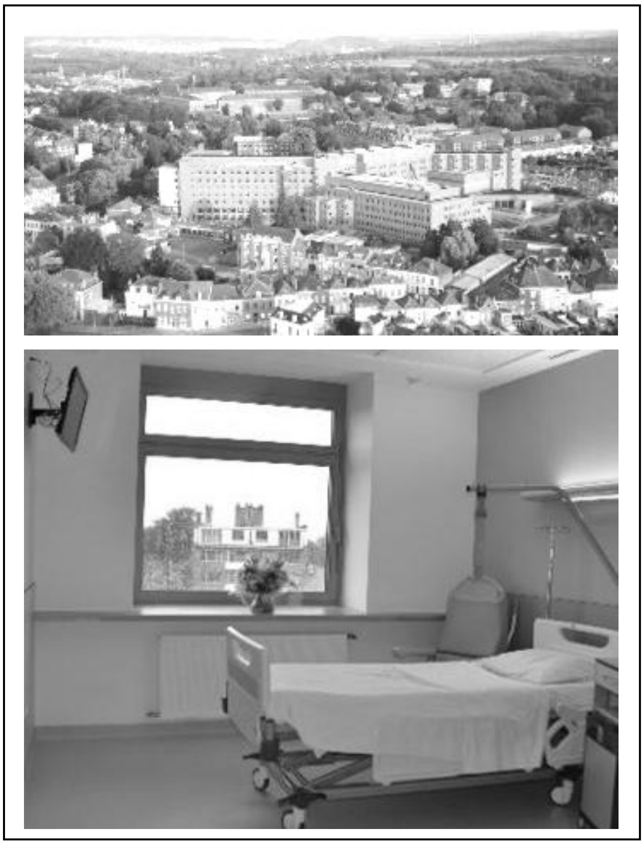


Figure 1. Illustrations for PWMC Hospital

This study focuses on single bed wards as shown below:

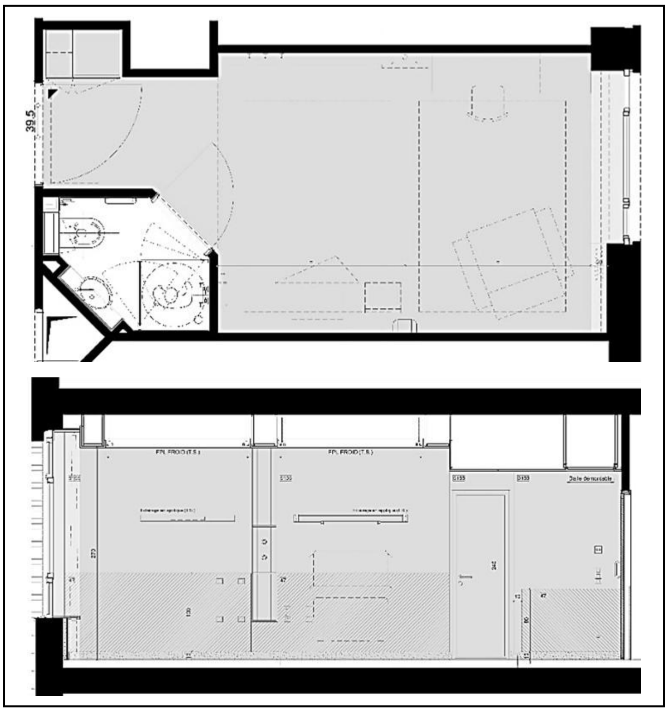


Figure 2. Single bed ward plan and section – PWMC

The chosen room situated in the 5th floor in the eastern façade as shown on figure below:

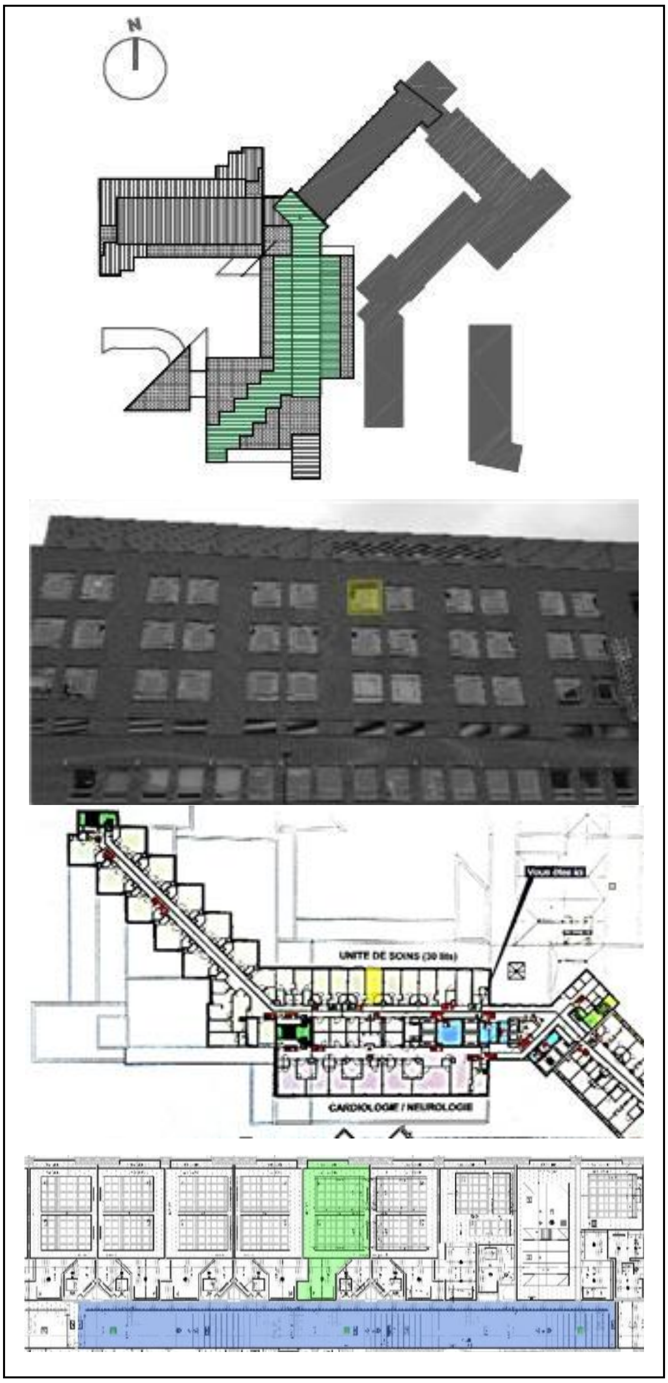


Figure 3. Chosen Ward Position – PWMC

III. Previous CFD Results

An analysis of ambient weather conditions at PWMC indicates the potential to utilize natural ventilation during summer. The hospital’s architectural design incorporated provisions for natural ventilation as a viable strategy to enhance indoor air quality. Observational data further reveal that patients frequently open windows during summer, reflecting both user behavior and the practical feasibility of implementing natural ventilation in patient wards.

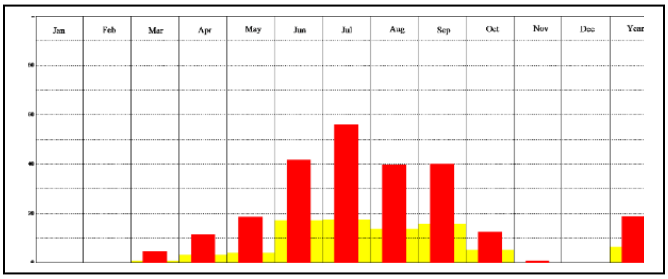


Figure 4. NV feasibility based on metrological analysis – PWMC

The window design implemented by the architect provides multiple opening configurations, offering flexibility in ventilation strategies. CFD simulations demonstrate that the upper-side window configuration yields the most favorable performance, particularly in reducing the age of air (AoA) and optimizing the predicted mean vote (PMV), thereby improving both indoor air quality and thermal comfort for patients.

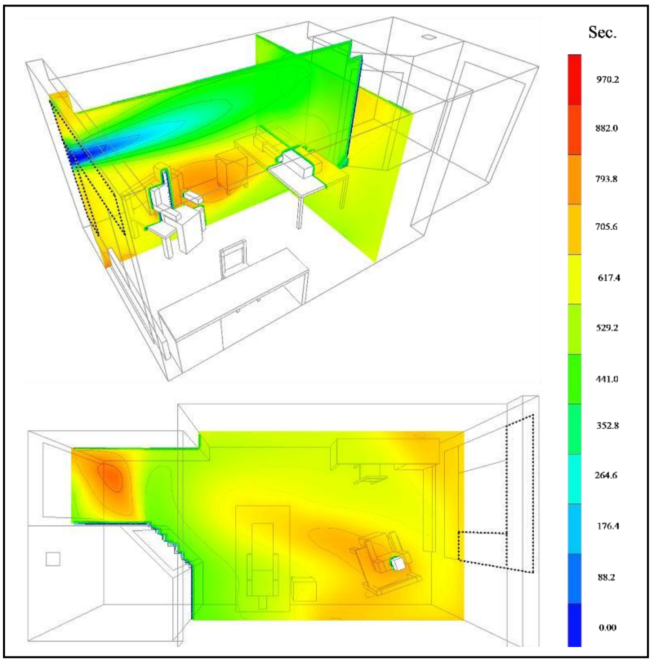


Figure 5. Age of air (0-970 sec) Upper Side Openings

IV. VALIDATION METHODOLOGY

An analysis of ambient weather conditions at PWMC indicates the potential to utilize natural ventilation during summer. The hospital's architectural design incorporated provisions for natural ventilation as a viable strategy to enhance indoor air quality. Observational data further reveal that patients frequently open windows during summer, reflecting both user behavior and the practical feasibility of implementing natural ventilation in patient wards.

A. *Local mean age of air: (the ISO 16000-8 Methodology)*

ISO 16000-8 provides standardized procedures for determining the local mean age of air in naturally or mechanically ventilated buildings using a single tracer gas. The local mean age of air is defined as the average time air has remained in a specific building zone, during which it accumulates contaminants. This parameter is a critical indicator of ventilation efficiency and indoor air quality. Tracer gas techniques rely on differentiating the air present in the room from the incoming fresh air [1].

The standard specifies the characteristics of suitable tracer gases: chemically inert, non-toxic, stable, odorless, non-flammable, non-explosive, and non-absorbent by surfaces. Commonly used gases include nitrogen, helium, argon, and CO_2. The principle involves either marking the existing air and monitoring its replacement or marking the incoming air and tracking its distribution. ISO 16000-8 describes several dilution procedures, including three main methods: the concentration decay method, the active homogeneous emission method, and the passive homogeneous emission method.

In this study, the concentration decay method was applied. This method marks the air in the test room with a tracer gas and measures the rate at which it is replaced by unmarked air, making it suitable for short-term ventilation assessments. Two systems are typically used for tracer gas injection:

- A graduated syringe or a container with controlled release.
- A compressed gas source with a critical orifice and an electronic mass flow controller or equivalent flow measurement device.

To ensure a uniform initial concentration, various mixing techniques may be employed:

- Fans to promote homogeneous mixing within study zones.
- Injection lines to distribute gas via manifolds or valves.
- Swinging doors to enhance air mixing after gas injection.

The gas concentration at a given point is recorded over time. The local mean age of air (τ_p) is calculated as the ratio of the integral of tracer gas concentration over time to its initial concentration at time t_0, as expressed in Equation (1):

$$\tau_p = \frac{\int_{t_0}^{\infty} C_t dt}{C_{t=t_0}} \quad (1)$$

Where τ_p is the local mean age of air; t is the time; C_t=t_0 is the initial tracer gas concentration at time t = t_0 (in $cm^3\ m^{-3}$ of tracer gas). If the test room has a total volume of V_R, the tracer gas volume V_I injected into the room is given by equation (2):

$$V_I = C_{t=t_0} \cdot V_R \quad (2)$$

The integral in equation (2) is evaluated from the measured tracer gas concentration history. The logarithm of the tracer gas concentration vs. time should be plotted and if this plot is linear from the time t = t_0, the local mean age of air can be calculated simply from the inverse of the absolute value of the slope. If it is not linear, a numerical integration technique, as the trapezoid method, could be used for the exponential decay [1].

B. *Window with fan & Door Open*

A CFD model of a typical single-bed patient ward was developed to calculate thermal comfort indices and the local mean age of air. To validate these simulations, the CO_2 decay method was employed in accordance with the ISO 16000-8 standard. The experimental validation configurations:

- Upper-side window with fan and door open,
- Upper-side window and door open,
- Middle window and door open,
- Side window and door open,
- Upper-side window with the door closed.

Each of these cases corresponded to an equivalent CFD simulation in OpenFOAM under identical boundary conditions. Additionally, the case involving the upper-side window and door open was modeled in DesignBuilder, providing an additional point of comparison with both OpenFOAM and field measurements.

The primary objective of these measurements was to validate the CFD results by comparing the mean age of air (AoA) obtained experimentally with those predicted by simulation. During the experiments, the ward was enriched with CO_2 until concentrations exceeded 5000 ppm. Air mixing was facilitated using a fan to ensure uniform distribution before initiating the ventilation scenario by opening the selected window(s), fan vent(s), and/or the door. The CO_2 concentration decay was monitored continuously until steady-state conditions were achieved.

Sensors were strategically placed on two horizontal planes along the y-axis, matching the planes considered in CFD simulations. The first plane included the patient bed and the side-opening window, while the second covered the window, entrance lobby, and door. This arrangement enabled accurate comparison between simulated and measured data under comparable spatial and thermal conditions.

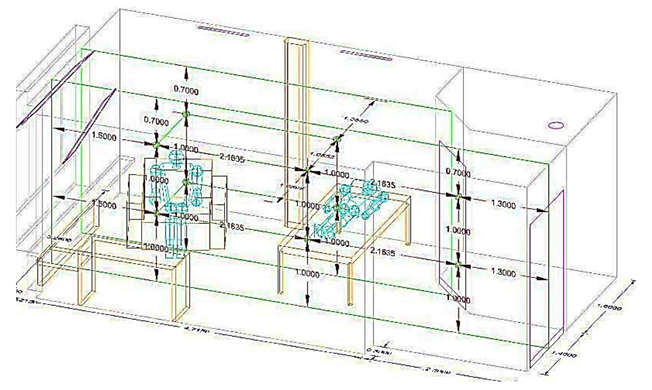


Figure 6. Sensors places and dimensions

V. EXPERIMENTAL PROTOCOL

To experimentally determine the local mean age of air in the selected ward, the CO_2 tracer gas decay method was employed, as it provides a reliable and straightforward approach for ventilation assessment. Two vertical cross-sectional planes were identified for analysis, with ten measurement points strategically distributed: four points along the first plane, which intersected the patient's bed and side window, and six points along the second plane, covering the corridor and door area.

A CO_2 cylinder (height: 127 cm, diameter: 22 cm, weight: 22.7 kg) was used to inject tracer gas into the sealed ward, increasing the CO_2 concentration from approximately 600 ppm to 8000 ppm for each test scenario. To ensure uniform distribution of the tracer gas, a fan was utilized for air mixing. Ten CO_2 sensors, sourced from two different brands, were installed at the designated points and connected to a data logging system to continuously record CO_2 concentration, temperature, and humidity ratio. Specifically, six wireless LGG-Newsteo sensors were placed in the corridor zone, while four Extech CO_2 Datalogger sensors were positioned in the patient bed zone. Additionally, a Testo 480 thermal comfort device was employed to measure airflow velocity, temperature, and pressure near the windows or fans, as well as 50 cm above the patient's pillow.

Two main categories were conducted for validation:

- Fan-assisted scenarios, where fans were placed at operable windows to regulate airflow from outside.
- Natural ventilation scenarios, where windows were opened without fan assistance in various configurations: upper window only, side window only, middle window, and combined upper and side windows.

An additional measurement was performed under conditions where the window remained closed and the door was open. Furthermore, a thermal camera was used to record wall surface temperatures to support thermal analysis.

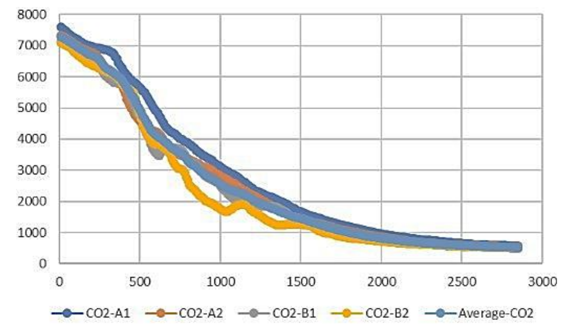
Figure 7. Sensors installation in the chosen ward

VI. RESULTS OF CFD VALIDATION VIA MEASUREMENTS

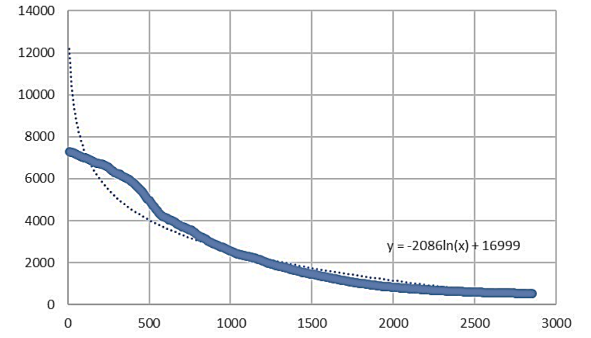
The purpose of these field measurements was to validate the CFD simulation results for a typical patient ward at the PWMC. This validation was achieved by conducting real-world measurements under identical boundary conditions and subsequently comparing these experimental results with the corresponding CFD simulation outputs.

A. *Window With Fan and Door Open*

The gas decay analysis for the bed-slice sensors indicates that the average local mean age of air, calculated as the area under the concentration–time curve, was approximately 16 minutes. The individual sensor readings were 17, 16, 16, and 15 minutes, respectively.



A. CO_2 decay – bed slice



B. Average CO_2 gas decay

Figure 8. AoA – With fan and door open 23/06/2016 1:40AM-2:40AM

These findings are consistent with the CFD simulation results obtained using OpenFOAM for the same slice location and under identical boundary conditions. The reported values represent an average, as the four sensors produced nearly identical readings. This agreement is further supported by the CFD output, where variations across the corresponding positions did not exceed two minutes, with an average of approximately 18 minutes. Specifically, the upper points in the CFD model correspond to the 1,162-second zone, while the lower points fall within the 996-second zone.

This close correlation between experimental measurements and CFD predictions demonstrates the reliability of the simulation model in accurately estimating the local mean age of air (AoA) under real-world conditions.

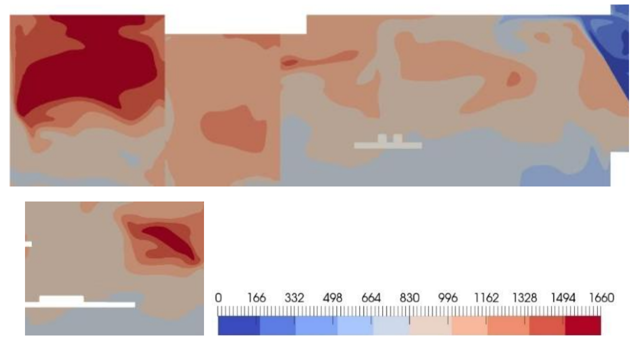
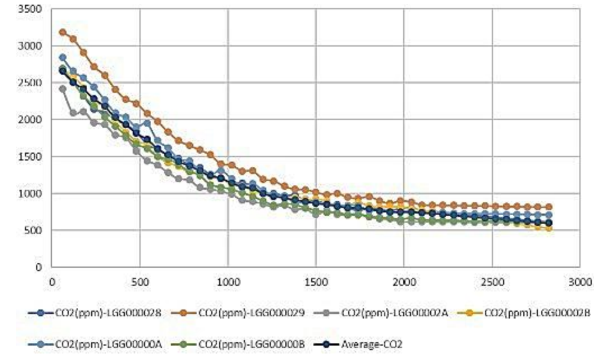
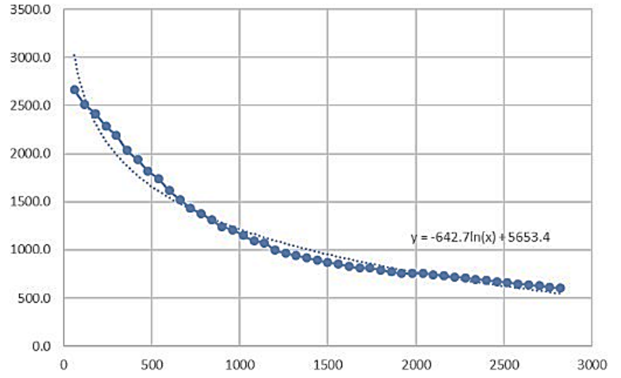


Figure 9. AoA – With fan and door open 23/06/2016 1:40AM-2:40AM

The results for the second slice also exhibit strong agreement with the field measurements, with an average local mean AoA of approximately 20 minutes. Minor discrepancies were observed, primarily due to the practical challenges of replicating identical conditions in the corridor zone. These differences can be attributed to the influence of measurement equipment and the inherent difficulty in controlling external corridor thermal conditions to match those in the simulation.



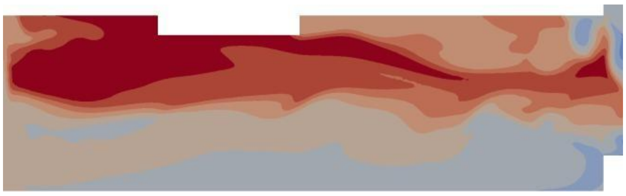
A. CO_2 decay – Corridor slice



B. Average CO_2 gas decay

Figure 10. AoA – With fan and door open 23/06/2016 1:40AM-2:40AM

The variation between the field measurements and CFD simulation results remained within two minutes.



A. Y-axis slice passing through corridor

B. Z-axis slice on 1 m height just above patients' bed

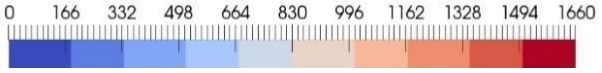
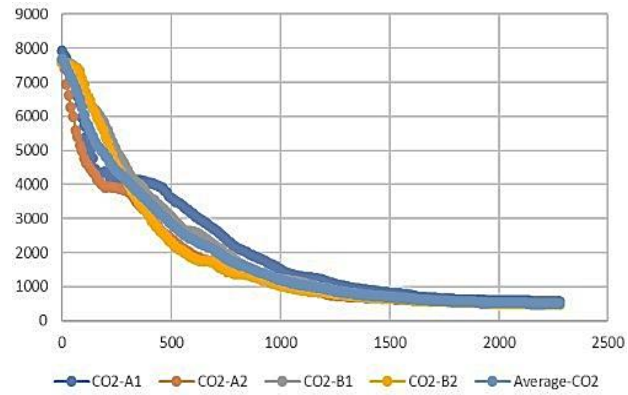


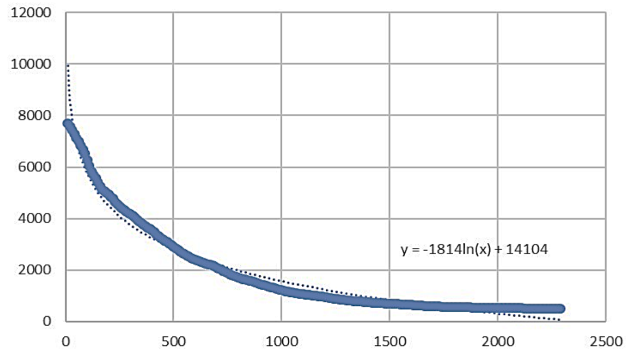
Figure 11. Age of Air AoA sections at patient ward - OpenFOAM

B. *Side Window and Door Open*

The gas decay analysis from the bed-slice sensors indicates an average local mean age of air of 9.12 minutes, with individual sensor readings of 9.80, 7.95, 9.87, and 8.88 minutes, respectively.



B. CO_2 decay – Corridor slice



B. Average CO_2 gas decay

Figure 12. AoA – side window & door open 23/06/2016 23:14PM-23:38PM

These results align closely with the CFD simulation outputs from OpenFOAM for the corresponding slice under identical boundary conditions, which yielded an average local mean age of air of 9.16 minutes. The similarity is further supported by the CFD data, where variations at individual positions did not exceed one minute, confirming strong consistency between experimental measurements and simulation predictions.

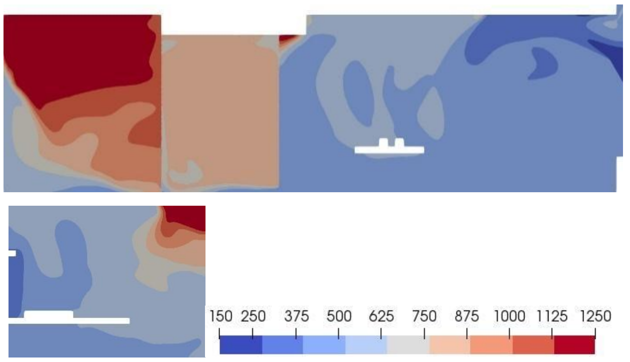
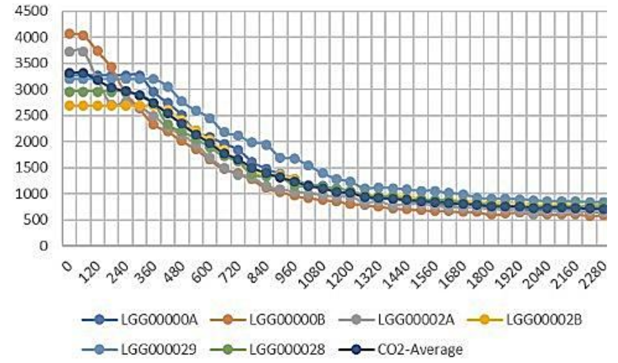
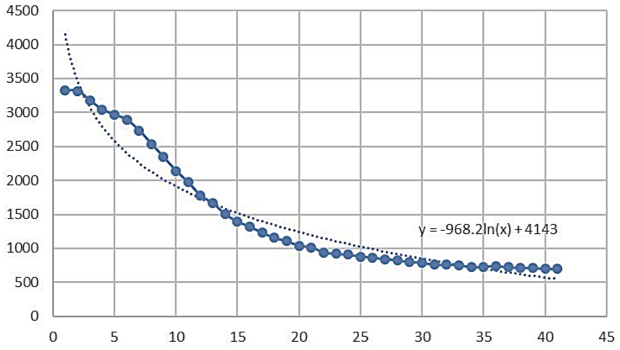


Figure 13. AoA side window & door open – Sec. at bed slice - OpenFOAM

The results for the second Y-axis slice also show good agreement with the field measurements. Due to the corridor's thermal conditions, influenced by building physics factors and the presence of a door facilitating airflow exhaust, it is more representative to compare the average values of the upper sensors with the corresponding CFD predictions for the same positions, and similarly, to compare the lower sensors with their adjacent CFD results.



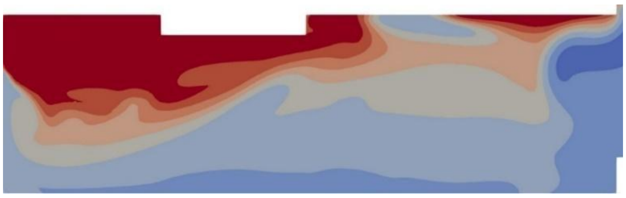
A. CO_2 decay – Corridor slice



B. Average CO_2 gas decay

Figure 14. AoA – Side window and door open 23/06/2016 23:00-23:44

The gas decay analysis for the upper sensors along the Y-axis slice indicates an average local mean age of air of 20.4 minutes, with individual sensor readings of 21.1, 21.0, and 19.1 minutes, respectively. In contrast, the lower sensors—also corresponding to positions represented in the Z-axis slice of the CFD simulation—recorded an average value of 15.0 minutes, with individual measurements of 12.8, 14.2, and 18.1 minutes.



A. Y-axis slice passing through corridor

B. Z-axis slice on 1 m height just above patients' bed

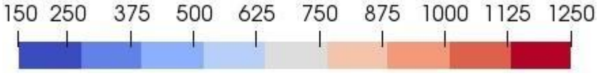
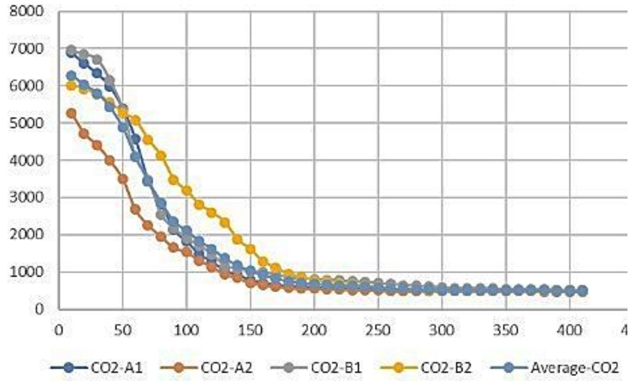


Figure 15. Age of Air AoA sections at patient ward – OpenFOAM

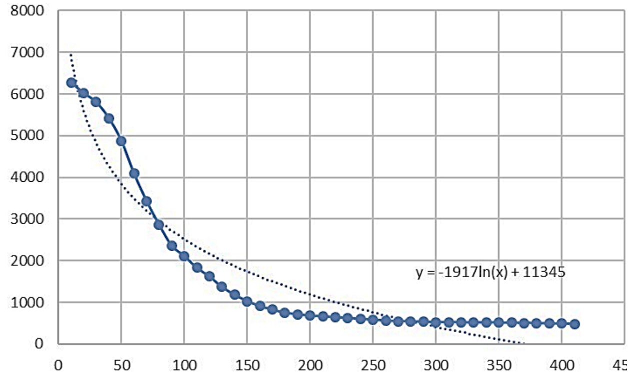
The corresponding CFD results for the same points indicate an average local mean age of air of 1,190 seconds (19.8 minutes) for the upper sensors and 750 seconds (13 minutes) for the lower sensors. The variation between the CFD predictions and field measurements does not exceed two minutes, which can be attributed to the practical challenges of maintaining consistent thermal conditions within the corridor during the experiments.

C. *Upper Side Window with Door Open*

The gas decay analysis from the bed-slice sensors indicates an average local mean age of air of approximately 2 minutes across the four measured points.



B. CO_2 decay – Corridor slice



A. CO_2 decay – Corridor slice

Figure 16. AoA – Upper side window & door open 23/06/2016 13:56-14:18

This result is consistent with the CFD simulation outputs obtained using OpenFOAM for the same slice under identical boundary conditions, which reported an average local mean age of air of approximately 3 minutes.

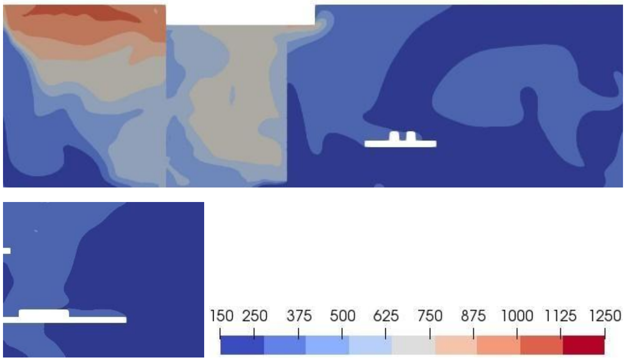
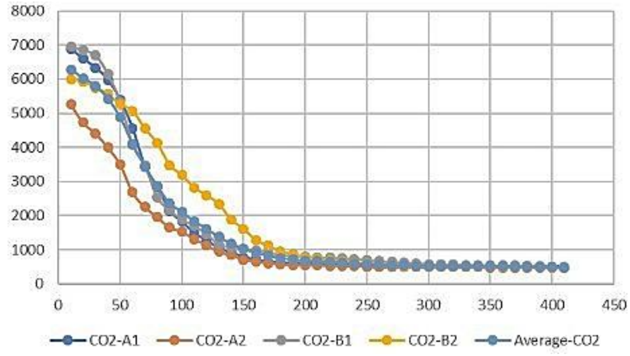
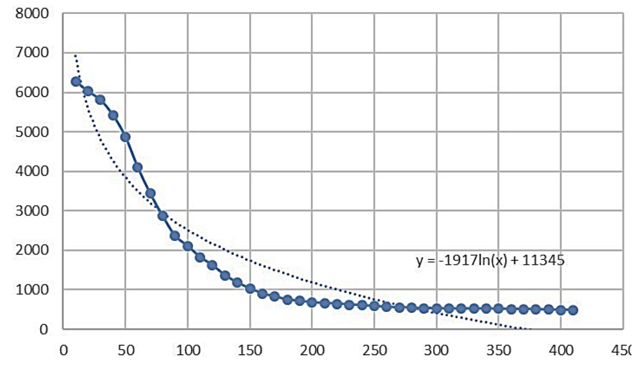


Figure 17. AoA Upper side window & door open –bed slice - OpenFOAM

The results for the second Y-axis slice indicate noticeable differences between field measurements and CFD predictions. The experimental averages of the local mean age of air were 11 minutes for the upper sensors and 8 minutes for the lower sensors, whereas the corresponding CFD simulations produced an average of approximately 5 minutes.



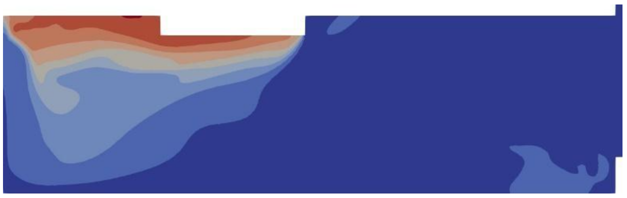
B. CO_2 decay – Corridor slice



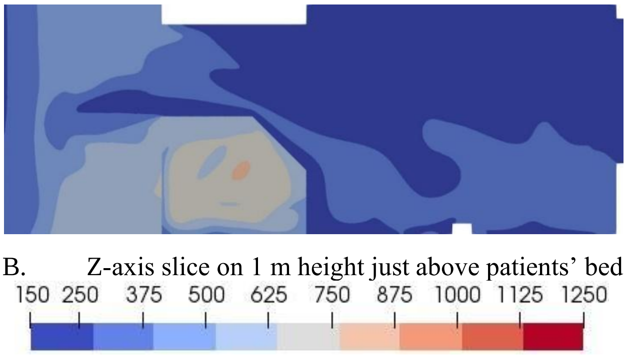
C. CO$_2$ decay – Corridor slice

Figure 18. AoA Upper side window and door open 23/06/2016 23:00-23:44

The analysis of the age of air (AoA) within the Y-axis slice of the corridor zone indicates that values do not exceed 4 minutes within the patient area but can reach up to 7 minutes in proximity to the door. The elevated air exchange rate in this region likely contributes to the difficulty of maintaining consistent boundary conditions in both CFD simulations and experimental measurements.



B. Y-axis slice passing through corridor



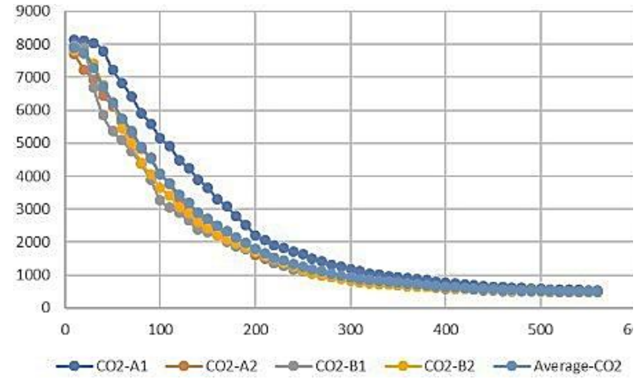
B. Z-axis slice on 1 m height just above patients' bed

Figure 19. Age of Air AoA sections at patient ward – OpenFOAM

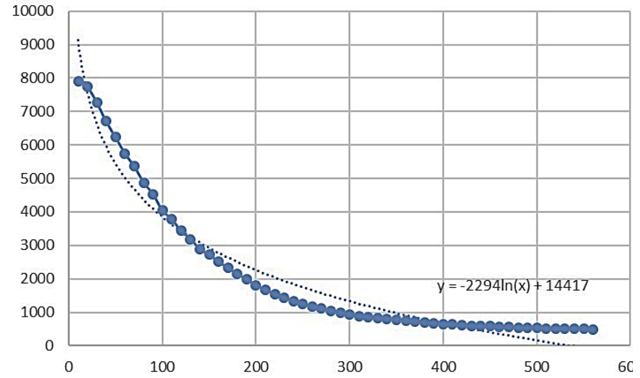
D. Middle Window and Door Open

The gas decay analysis at the bed-slice sensors indicates that the average age of air, calculated as the area under the decay curve, is approximately 2.5 minutes. The individual sensor readings were 2.8, 2.3, 2.1, and 2.3 minutes, respectively.

The CFD simulation results are notably higher than the experimental measurements. The computed average mean age of air is approximately 6 minutes, which is nearly double the value obtained from the field measurements. This discrepancy suggests that, under high-velocity conditions, the CFD model represents airflow with reduced momentum. This outcome is expected due to the modeling approach employed, where the window was connected to an 8.00 m external box, partially incorporating external boundary conditions on its sides. While the model performs adequately overall, this configuration tends to reduce airflow speed when the exposed area to the outdoors increases.



C. CO$_2$ decay – Corridor slice



B. Average CO$_2$ gas decay

Figure 20. AoA – Middle window & door open 24/06/2016 00:05-00:15

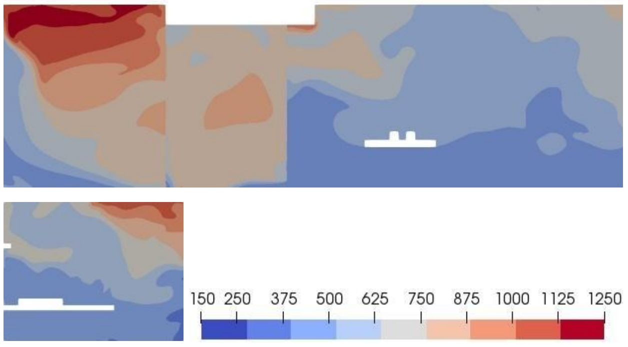
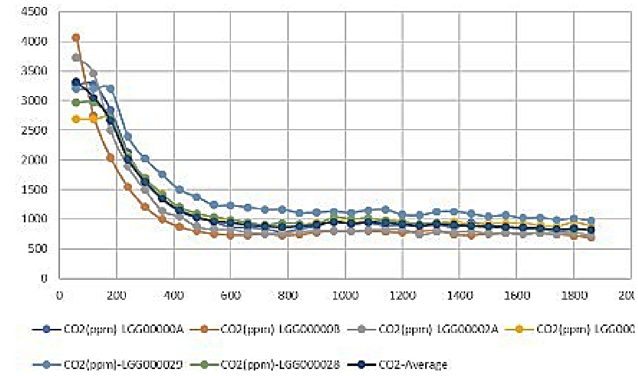
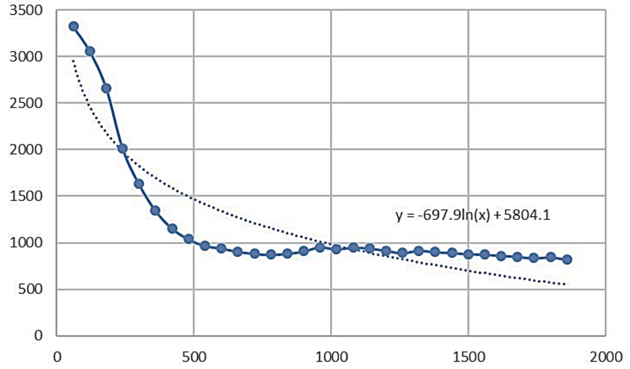


Figure 21. AoA Middle window & Door open –bed slice - OpenFOAM

The results for the second Y-axis slice show good agreement between CFD simulations and experimental measurements. The experimental averages of the local mean age of air were 13.5 minutes for the upper sensors and 9.5 minutes for the lower sensors, while the corresponding CFD simulation produced an average value of 12.5 minutes.



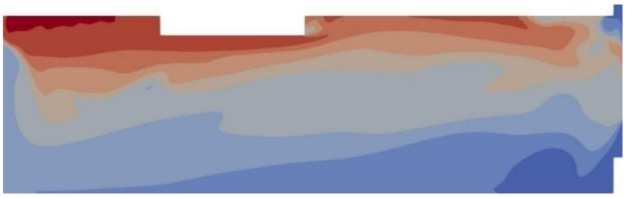
C. CO_2 decay – Corridor slice



B. Average CO_2 gas decay

Figure 22. AoA – Middle window and door open 24/06/2016 06:00-00:39

The age of air (AoA) distribution along the Y-axis slice in the corridor exhibits a regular laminar pattern. The CFD simulation results closely match the experimental measurements, as described above, demonstrating the model's ability to accurately capture airflow behavior in this zone.



D. Y-axis slice passing through corridor

B. Z-axis slice on 1 m height just above patients' bed

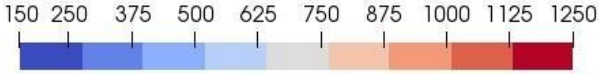


Figure 23. Age of Air AoA sections at patient ward – OpenFOAM

VII. Field Measurements vs OpenFOAM vs DesignBuilder Results

A series of measurements were conducted to evaluate CO_2 decay and thermal comfort in a typical ward located on the fourth floor. The room situated at the middle of the corridor. The experiments were carried out in collaboration with the PWMC construction team and hospital staff from 21st to 24th June 2016. For selected CFD validation cases, fans were used to control the airflow from the windows, ensuring that experimental conditions closely matched the boundary conditions applied in the OpenFOAM simulations. Additional measurements were performed to further verify and align the field data with the CFD simulation results.

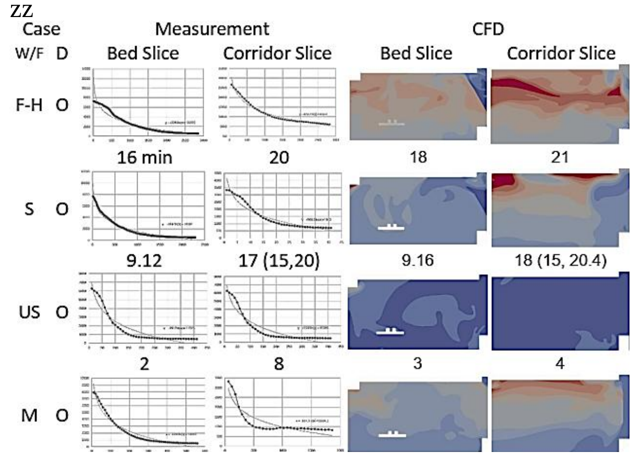


Figure 24. Age of Air – Field measurement VS OpenFOAM results

The DesignBuilder CFD simulation tool was initially employed to generate preliminary results prior to developing a detailed CFD model using Ansys (for meshing) and OpenFOAM (for CFD simulation). DesignBuilder provided a first assessment of airflow and thermal conditions, which was subsequently refined through intensive analysis in the Ansys–OpenFOAM workflow. The following table presents a summarized comparison of the simulation tools in this study:

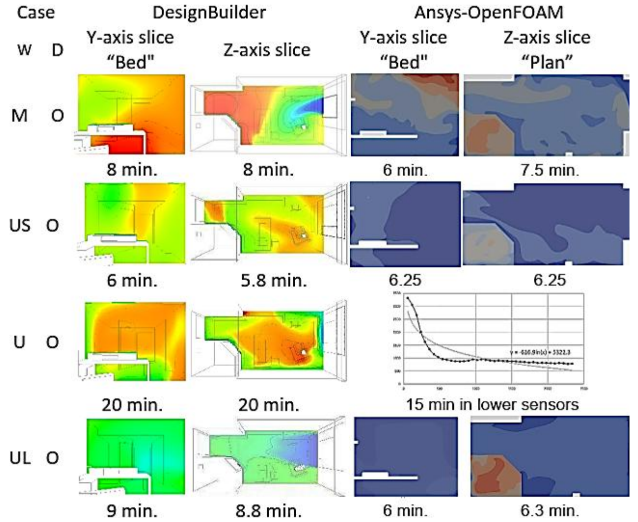


Figure 25. Age of Air – DesignBuilder VS OpenFOAM results

The comparison presented in the table demonstrates a strong similarity between the results obtained from DesignBuilder and OpenFOAM. In the DesignBuilder model, the presence of a second seated occupant slightly altered the airflow distribution pattern; however, the overall timescales remained comparable. While OpenFOAM provides higher accuracy and is better suited for investigating precise aspects of airflow and ventilation, such detailed modeling is often unnecessary for preliminary architectural design decisions. In early design stages, factors such as layout, functional requirements, and other design considerations may have a greater impact than the fine-scale accuracy of natural ventilation predictions.

The use of CFD should therefore be guided by the expertise of a CFD specialist, considering both the feasibility of detailed studies and the objectives of the project. Additionally, field measurements can sometimes yield more realistic and reliable results than simulations, highlighting the importance of strategic decision-making by both the CFD expert and senior researchers before selecting the modeling approach.

VIII. CONCLUSION

The CFD models developed using DesignBuilder and OpenFOAM have been validated against field measurements in a typical patient ward at PWMC, demonstrating strong agreement with minor variations in the corridor zone. This validation confirms that the models can be reliably used to investigate the influence of varying indoor and outdoor conditions, including air temperature and velocity, on the local mean age of air and overall ventilation performance. The study highlights the value of combining simulation and experimental data to support evidence-based design decisions in hospital ventilation planning.

IX. DISCUSSION

Indoor air quality (IAQ) in hospitals is crucial for patient health, comfort, and infection control. The local mean age of air (AoA) serves as a key indicator of ventilation efficiency, and ISO 16000-8 provides a standardized tracer gas method for its determination [12–15].

This study validated CFD predictions against experimental CO_2 decay measurements in a naturally ventilated hospital room under various window and door configurations. Results indicated strong agreement between field measurements and simulations, with differences of about 10%. While CFD offers flexibility for scenario testing and reduces time and cost, experimental methods remain essential for real-world validation.

The findings confirm that combining CFD with tracer gas measurements provides a robust framework for evaluating and optimizing natural ventilation in healthcare facilities, ultimately improving IAQ and occupant comfort.

NOMENCLATURE

Symbols :		VR	Room total Volume
CFD	Computational Fluid Dynamics	CO2	Carbon Dioxide
PWMC	Picardy Wallonia Medical Center	ppm	part per million
AoA	Age of Air	**Indices / Exponents :**	
NV	Natural Ventilation	H	Height
τ_p	Local Mean Age of Air	D	Diameter
t	Time	**Units :**	
c	tracer gas Concentration $cm^3\ m^{-3}$	Area	m^2
V^R	Room total Volume	Length	cm, m
V_I	tracer gas Volume	Weight	kg

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