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Optimizing Thermal Comfort and Air Quality in University Classrooms: A CFD-Based Comparative Analysis of HVAC Configurations

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Abstract – This study evaluates the thermal comfort and airflow performance of two HVAC configurations in a university lecture room to optimize indoor environmental quality and enhance learning conditions. Conducted in Classroom 1303 at October 6 University, Egypt, the research utilized computational fluid dynamics (CFD) simulations with ANSYS® fleunt to analyze thermal and airflow distribution under two setups. Case 1 featured a free-standing air conditioner with a single inlet and outlet, while Case 2 employed a concealed ceiling-mounted system with two inlets and outlets. The results revealed significant differences between the systems. Case 1 showed uneven cooling, with a temperature gradient of 6–8°C between the front and rear sections, inconsistent airflow velocities of 0.5–0.7 m/s near the windows, and poor air mixing. Relative humidity ranged between 32–42%, reflecting further inconsistencies. In contrast, Case 2 achieved a uniform temperature gradient of 2–3°C, balanced airflow velocities of 0.3–0.5 m/s, and stable relative humidity between 38–42%. Thermal comfort analysis using Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices highlighted Case 2's superior performance, with PPD values consistently below 10%, while Case 1 showed discomfort levels exceeding 25% in localized areas. These findings underscore the concealed ceiling-mounted system's ability to deliver consistent thermal comfort, better airflow distribution, and stable environmental conditions compared to the free-standing air conditioner. This research offers valuable insights for architects and engineers in designing HVAC systems that enhance indoor environmental quality in educational spaces, with future studies recommended to focus on energy efficiency and experimental validation for further optimization.

Keywords: Thermal Comfort, Classroom Environment, Computational Fluid Dynamics, Ventilation Strategies, HVAC Systems.

1 Introduction

Thermal comfort, a critical aspect of human well-being and productivity, has garnered significant attention in various fields ranging from building design and environmental engineering to occupational health and psychology. It refers to the subjective perception of thermal conditions by individuals, influenced by factors such as temperature, humidity, air movement, and clothing. Achieving optimal thermal comfort is essential, as discomfort can lead to reduced cognitive performance, increased stress, and overall dissatisfaction among occupants[1].

Understanding thermal comfort involves exploring not only the physical parameters of the environment but also the complex interplay between environmental conditions and individual preferences, physiological responses, and cultural backgrounds. Standards such as ISO 7730 and ASHRAE Standard 55 provide guidelines for assessing and achieving thermal comfort in indoor environments, emphasizing the importance of maintaining a balance between energy efficiency and occupant satisfaction [1] [2].

In recent years, advancements in technology and simulation tools have enabled more detailed investigations into thermal comfort, allowing researchers and practitioners to analyze complex thermal environments and optimize building designs for human comfort and well-being. Computational fluid dynamics (CFD) simulations, in particular, have become indispensable tools for predicting airflow patterns, temperature distributions, and thermal comfort indices in various spaces, including classrooms, offices, and residential buildings [3].

This introduction sets the stage for further exploration into thermal comfort, highlighting its significance in the design and operation of built environments and the evolving methodologies for assessing and achieving optimal comfort conditions. By delving into the intricacies of thermal comfort, researchers and practitioners can better understand human-environment interactions and develop strategies to create healthier, more productive, and sustainable indoor environments.

The study also incorporates key parameters related to thermal comfort, including air temperature, mean radiant temperature, air velocity, and humidity, which are continuously monitored and analyzed during the simulation process. To quantify the perceived comfort levels of occupants, the study utilizes common thermal comfort indices such as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). These indices provide a numerical assessment of the comfort levels based on the environmental conditions within the room, helping to gauge the effectiveness of each air conditioning case in improving the overall thermal comfort.

Figure 1 illustrates the relationship between the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD), key metrics in thermal comfort studies. The curve shows that at a PMV of 0 (neutral thermal sensation), the PPD reaches its minimum value of 5%, indicating the optimal thermal comfort condition where the least number of occupants are dissatisfied. As the PMV deviates positively or negatively (indicating warmer or cooler sensations), the PPD increases, reflecting a higher percentage of discomfort among occupants.

To assess the thermal comfort levels within the indoor swimming pool facility, Fanger (Fanger,1970) proposed the Predicted Mean Vote (PMV), and it is defined as an index that anticipates the mean reaction of a large group of people based on the ASHRAE thermal sensation scale. PMV can be estimated using the six essential thermal environment factors, which represent combinations of environmental and personal data, as specified in ASHRAE Standard 55 (ASHRAE,2010)[1]. the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) parameters were calculated. The PMV is determined using the equation[14]:

$$PMV = [0.352e^{-0.042M} + 0.032]\big(M - 0.35(43 - 0.061M - Pa) - 0.42(M - 50) - 0.0023M(44 - Pa) - 0.0014M(34 - T_a) - 3.4 \times 10^8 f_{cl}((T_b + 273)^4 - (T_a + 273)^4) - f_{cl}h(T_b - T_a)\big) \quad (1)$$

$$PPD = 100 - 95e^{-[0.03353PMV^4 + 0.2179PMV^2]} \quad (2)$$

Where:

- PMV = Predicted mean vote;
- PPD = Predicted percentage of dissatisfied,
- M= $Metabolic\ rate = 43.741 \frac{Kcal}{m^2.hr}$;
- Pa= vapor pressure, mmHg;
- T_a= $air\ temperature\ near\ surface$, °C;
- T_b=$Body\ surface\ Temperature$ °C;
- F_{cl}=$clothing\ area\ factor$ 1.15;
- H= $8.95V^{.5} = Heat\ transfer\ coefficient, \frac{Kcal}{hr.m^2.°C}$ and
- V= $Localair\ velocity, m/s$.

These equations allow for the evaluation of thermal comfort levels based on various parameters, providing insights into the occupants' likely perception of the thermal conditions within the education facility.

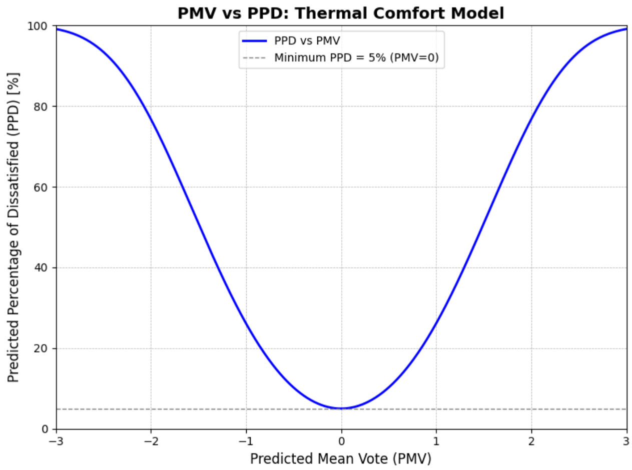


Figure 1:Relation between PMV (x-axis) and PPD (y-axis)

1.1 Previous Research

The literature review provides a comprehensive examination of existing research and scholarly works relevant to the topic at hand. It serves as a foundation for understanding the current state of knowledge, identifying gaps, and informing the research methodology and findings of the present study.

ElShimi et al.[6] In this study, the airflow distribution and movement of coronavirus particles during normal breathing and sneezing in classrooms were investigated using a CFD model developed in ANSYS® 2022R2. The primary objective was to explore methods to control the spread of the virus, facilitating academic activities while addressing the challenges posed by the pandemic. Multiple turbulence models were employed in experiments to assess their accuracy compared to empirical data and determine the optimal mesh density in the classroom.

Optimal ventilation was achieved by introducing fresh air through side wall inlets positioned 1 meter above the floor, with air exiting from ceiling outlets arranged in two rows. A ventilation rate of 4 air changes per hour (ACH) was found to strike a balance between effective virus control and energy efficiency. Additionally, a novel transparent cabin design equipped with a high-efficiency particulate air (HEPA) filter was developed to contain sneeze particles within the cabin and recirculate filtered air back into the classroom at varying fan speeds. This cabin design effectively prevented the transmission of sneeze particles to other students in the classroom, as demonstrated in the study.

Kokash et al. [7] This study involved conducting a numerical simulation of a classroom's indoor environment using Fluent Ansys to assess the efficacy of air filtration boxes in preserving indoor air quality (IAQ) and thermal comfort while mitigating the spread of airborne particles. The simulation focused on analyzing the dispersion of aerosol particles emitted by occupants, airflow patterns, and pollutant concentration within a standard classroom equipped with a ventilation system comprising supply and return air diffusers along with air filtration boxes. The outcomes underscored the substantial influence of air filtration box placement and positioning on both IAQ and thermal comfort. It was observed that the strategic placement of air filtration boxes can yield significant improvements in these parameters. Surprisingly, the study revealed that a higher number of filtration boxes doesn't necessarily translate to better outcomes; instead, as few as two strategically positioned filtration boxes can deliver comparable effectiveness. These insights provide valuable guidance for researchers seeking to optimize ventilation strategies for similar classroom settings.

Ascione et al. [8]The study aimed to offer practical guidance for renovating educational buildings, specifically university classrooms, to ensure they are safe and sustainable indoor environments in light of the 2020 SARS-CoV-2 pandemic. Recognizing the need to reimagine classrooms and common areas in response to the global emergency, the research focused on a real case study involving the architectural and technological refurbishment of an Italian university building located in Campobasso, South Italy, characterized by a cold climate. The overarching objective was to enhance the quality and safety of classrooms by proposing a comprehensive retrofit design approach.

Lakhdari et al. [9] This study exemplified the application of such an approach in optimizing the thermal, lighting, and energy performance of a middle school classroom in a hot and dry climate. By employing a parametric approach and evolutionary multi-objective computation through the Octopus plug-in for Grasshopper, the study explored various combinations of window-to-wall ratios, wall materials, glass types, and shading devices to identify potential solutions that strike a balance between daylight provision, thermal comfort, and energy efficiency. The findings revealed that adjustments to building envelope parameters could yield enhancements in useful daylight illuminance, adaptive thermal comfort, and energy efficiency. Moreover, the study examined solutions tailored to different building orientations, offering insights into recommended window-to-wall ratios for school buildings in hot and dry climates. Overall, the results underscored the efficacy of optimization methodologies in informing early-stage building design processes, facilitating a deeper understanding of how building envelopes can be customized to ensure optimal performance in terms of both comfort and energy efficiency.

Arpino et al. [10] The study addresses the significant concern of infection transmission through airborne droplets in indoor settings, particularly in densely populated environments like schools and universities. It underscores the necessity of appropriately designing Heating, Ventilation, and Air Conditioning (HVAC) systems to mitigate transmission risks effectively. Utilizing 3D Computational Fluid Dynamics (CFD) simulations, validated against velocity measurements, the research delves into the temporal dispersion patterns of airborne droplets emitted from the teacher's position during a 2-hour lecture session. With a focus on informing HVAC system design and operation, the study explores the impact of varying air supply rates on aerosol concentration within an unoccupied lecture room.

1.2 Problem statement

Thermal discomfort within the lecture room is a significant issue, primarily attributed to the heat generated by two large windows. Measurements conducted on 11-12-2024 revealed that the windows reached surface temperatures as high as 31°C during the winter season. This localized heat substantially raised the overall room temperature to 26.7°C, as depicted in Figure 2, which includes thermal imaging results. Figure 3 further illustrates this thermal imbalance through a dual-perspective visualization combining a visible-light photograph and a thermal image. The uneven temperature distribution within the room, exacerbated by the lack of an air conditioning system, contributes to inadequate air circulation, creating a learning environment that is thermally uncomfortable for students.

To evaluate the thermal performance of the lecture room and pinpoint the primary sources of heat, advanced diagnostic tools were employed. The FLIR TG165-X [4] thermal imaging camera played a critical role in identifying and analyzing thermal anomalies. Equipped with an IR resolution of 80 × 60 pixels, thermal sensitivity of <70 mK, and a temperature measurement range of -25°C to 300°C, the camera provided precise evaluations of heat sources, particularly the windows. Its MSX® image enhancement feature enabled detailed thermal and visual imaging, offering clear insights into areas with significant heat accumulation.

Additionally, the Fluke 62 MAX+ [5] Handheld Infrared Laser Thermometer was utilized to accurately measure surface temperatures. With a wide temperature range of -30°C to 650°C and a 12:1 distance-to-spot ratio, this device allowed precise readings of thermal conditions in the room. Its robust design, featuring IP54 dust and moisture resistance and 3-meter drop-tested durability, ensured reliable measurements in diverse conditions. The thermometer's dual lasers and backlit display enhanced usability, while its high and low alarms efficiently flagged temperature variations outside acceptable limits.

These assessments underscore the pressing need for improved thermal management within the lecture room. The combination of high window temperatures and inadequate air circulation significantly disrupts thermal comfort, adversely affecting student focus and overall learning outcomes. Addressing these challenges requires the implementation of effective thermal management solutions, such as the installation of air conditioning systems, to create a conducive and comfortable learning environment.

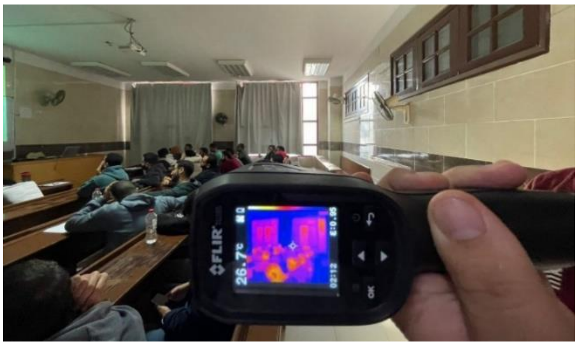


Figure 2: Dual perspective of the lecture room and thermal camera capturing the temperature distribution inside the lecture room.

Figure 3: Measuring lecture large windows temperature during winter season using IR thermometer

1.2.1 Lecture Room Description

The enclosure comprises the university lecture room under investigation accommodates up to 50 students, with a total of 12 wooden benches, each coated with a layer of plastic paint. The layout of the room is designed to maximize student seating while maintaining accessibility for the lecturer. The room features two large windows positioned to face the sun during working hours, which significantly contributes to the heat levels inside the room. In addition to these, there are two smaller windows intended to serve as ventilation vents, opening into the main corridor. However, these small windows are permanently closed due to an unreachable locking mechanism, hindering proper airflow. The teaching area is equipped with a high bench for the lecturer, which includes a projector and a whiteboard for instructional use. The door to the room is a wooden door with an opening width of 1.5 meters, providing the only access point to the room.

1.3 Presented Study

This research focuses on lecture room at October 6 University located in Giza, Egypt. Considered is a enclosure with complex geometry, measuring (10 m,12.6 m,3 m) in size. As illustrated in Figure 5 , The study is designed with two distinct cases to evaluate the impact of different air conditioning setups on thermal comfort in the lecture room. The study includes the creation of detailed CAD models as shown in Figure 7 of the room and subsequent Computational Fluid Dynamics (CFD) simulations. These analyses aim to determine which configuration offers the optimal solution for improving thermal comfort within the lecture room.

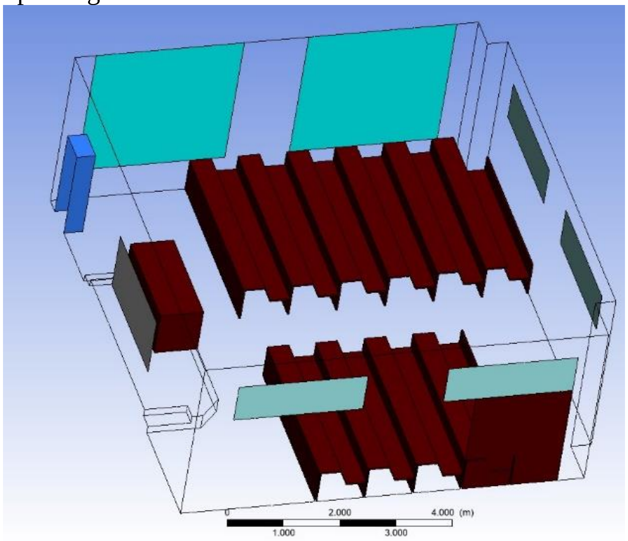
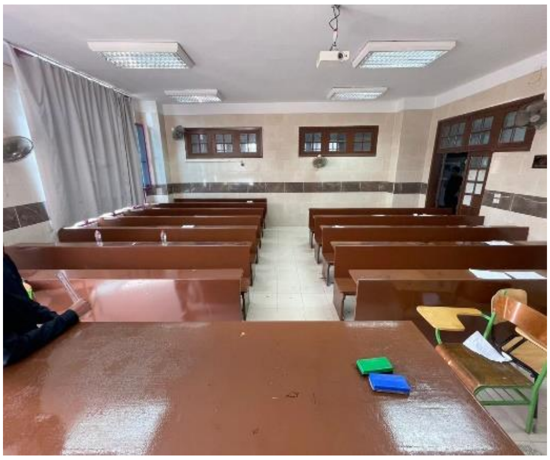


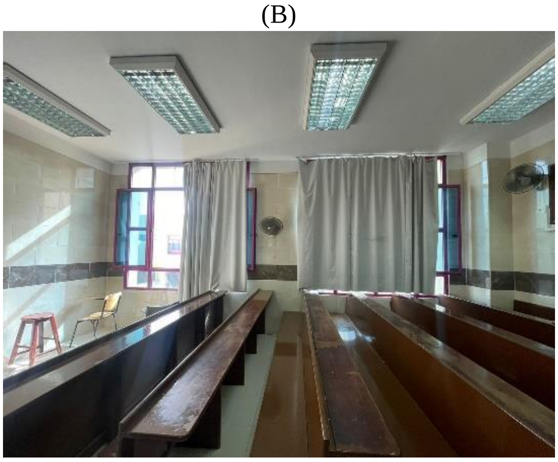
Figure 4: Isometric CAD model of the lecture room



(A)

(B)

(C)



(D)

Figure 5 : The real geometry of Lecture Room (1303) at Faculty of Engineering at October 6 University

2 Methods:

This study is dedicated to investigating thermal comfort within university classrooms through a numerical simulation approach. The methodology adopts a computational framework to evaluate and assess various factors influencing the thermal conditions of selected classroom environments. Using ANSYS Fluent, a specialized Computational Fluid Dynamics (CFD) software, the study conducts detailed numerical simulations to model the thermal behavior of the lecture room. The simulation environment accurately represents the geometry, dimensions, and layout of the room, ensuring a realistic analysis of the thermal dynamics and their impact on occupants' comfort through a 3 CFD contours as shown in Figure 7 presenting the details needed to write a correct conclusion.

The governing equations utilized in this numerical simulation study are based on principles of fluid dynamics and heat transfer. These equations form the foundation for modeling the behavior of air and heat within the simulated classroom environment. The primary governing equations include:

Navier-Stokes equations: These equations describe the conservation of momentum for fluid flow and are fundamental to simulating airflow patterns within the classroom. They are expressed in vector form as the conservation of momentum in the x, y, and z directions [11][7].

$$\partial \rho u/\partial t + \partial(\rho u^2)/\partial x + \partial(\rho uv)/\partial y + \partial(\rho uw)/\partial z = -\partial p/\partial x + \mu(\partial^2 u/\partial x^2 + \partial^2 u/\partial y^2 + \partial^2 u/\partial z^2) + Fx \quad (3)$$

Energy equation: The energy equation governs the transfer of thermal energy within the classroom. It accounts for conduction, convection, and radiation heat transfer mechanisms, as well as internal heat sources such as occupants and electronic devices.

$$\rho(\partial h/\partial t + u\partial h/\partial x + v\partial h/\partial y + w\partial h/\partial z) = k(\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2 + \partial^2 T/\partial z^2) + Q \quad (4)$$

Continuity equation: The continuity equation expresses the conservation of mass for fluid flow and ensures that mass is conserved within the simulated domain. It is used to model the flow of air and other fluids within the classroom.

$$\partial \rho/\partial t + \partial(\rho u)/\partial x + \partial(\rho v)/\partial y + \partial(\rho w)/\partial z = 0 \quad (5)$$

Species transport equation: In cases where the simulation includes the dispersion of airborne contaminants or particles, the species transport equation is employed to track the concentration of these species within the airflow.

$$\partial(\rho\varphi)/\partial t + \partial(\rho u\varphi)/\partial x + \partial(\rho v\varphi)/\partial y + \partial(\rho w\varphi)/\partial z = \partial/\partial x(\Gamma\varphi\, \partial\varphi/\partial x) + \partial/\partial y(\Gamma\varphi\, \partial\varphi/\partial y) + \partial/\partial z(\Gamma\varphi\, \partial\varphi/\partial z) + S\varphi \quad (6)$$

By solving these governing equations numerically using computational fluid dynamics (CFD) techniques, the behavior of airflow and thermal comfort parameters such as temperature, velocity, and humidity can be accurately predicted within the simulated classroom environment. These predictions are essential for assessing the effectiveness of different ventilation strategies and HVAC systems in maintaining optimal thermal comfort conditions for occupants.

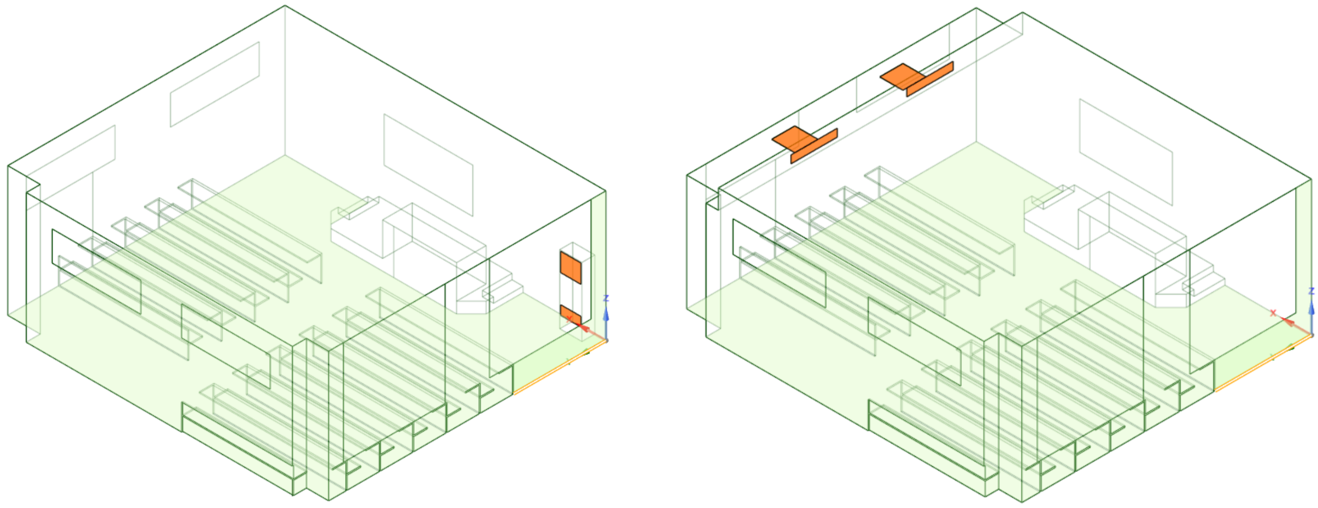
1.4 Boundary conditions

Boundary conditions are defined to simulate realistic environmental conditions, including external temperatures, solar radiation, and ventilation systems. Internal heat sources, such as occupants and electronic equipment, are also incorporated into the simulation to reflect typical classroom scenarios.

The simulation setup included specific boundary conditions and environmental factors to accurately evaluate the thermal performance and airflow distribution. The internal walls and indoor windows were assigned a constant temperature of 30°C, representing typical classroom thermal conditions. The outdoor walls and windows were subjected to solar radiation based on the global position of the building. The geographic location used in the model was set at a longitude of 29.58°, latitude of 30.56°, and a time zone of GMT+2, corresponding to June 21st at 1:00 PM—a peak solar radiation period.

The mesh orientation was carefully aligned with cardinal directions for accurate solar radiation modeling. The north direction was represented with vector components x: -0.5, y: 0.5, z: 0, while the east direction was represented as x: 0.5, y: 0.5, z: 0. The simulation utilized the surface-to-surface radiation (S2S) model to account for heat transfer between surfaces, ensuring precise calculation of radiative heat exchanges influenced by solar loading.

This setup allowed the study to replicate realistic environmental and thermal conditions, ensuring the reliability of the CFD results in assessing HVAC performance and classroom thermal comfort.



Case 1 Case 2

Figure 6: HVAC Configurations for Classroom Analysis (Case 1: Free-Standing Unit, Case 2: Concealed Ceiling Unit)

Table 1: The description of the 2 configurations

Case	Inlet			Outlet			Solution
	Dimension [mm]	No. of unit	Location	Dimension [mm]	No. of unit	Location	
1	550×500	1	On the ceilling	550×250	1	On the floor	CFD equations of fluent software had converged at 1×10^{-3}
2	1200×200	2		600×600	2		

Table 2: Skewness mesh metrics spectrum

Excellent	Very Good	Good	Acceptable	Bad	Unacceptable
0-0.25	0.25-0.50	0.50-0.80	0.80-0.94	0.95-0.97	0.98-1.00

Table 3: Orthogonal quality mesh metrics spectrum

Unacceptable	Bad	Acceptable	Good	Very Good	Excellent
0-0.001	0.001-0.14	0.15-0.25	0.20-0.69	0.70-0.95	0.95-1

To ensure high-quality mesh, the study assessed the orthogonal quality and skewness values for different grid sizes,

1.5 Boundary conditions of the configurations

The analysis investigates two configurations for HVAC systems in a university classroom to evaluate their thermal performance and air distribution efficiency. Figure 6 illustrates the layout of both configurations, while Table 1 provides detailed descriptions of their specifications.

In Case 1, a free-standing air conditioner with a capacity of 5 HP is installed near the large windows, which are exposed to direct sunlight during working hours. The system is designed to deliver cool air from the ceiling and has a single outlet located on the floor for return air. The air conditioner features an inlet measuring 550 mm × 500 mm and an outlet dimension of 550 mm × 250 mm.

In Case 2, a concealed air conditioning unit is mounted near the ceiling, designed to distribute cool air uniformly from the top of the room. This setup includes two inlet units, each measuring 1200 mm × 200 mm, and two outlet units, each 600 mm × 600 mm, strategically placed to enhance cooling efficiency and air circulation. The CFD equations in Fluent software for both configurations converged at a tolerance level of 1 × 10^(-3), ensuring reliable simulation results.Mesh Quality

The mesh quality plays a critical role in ensuring accurate CFD simulation results. For both Case 1 and Case 2, the mesh was carefully generated and evaluated based on element count, skewness, and orthogonal quality. In Case 1, the mesh consisted of 758,087 elements, with skewness values kept under 0.8 to maintain element shape quality, and an orthogonal quality above 20%, indicating a well-structured and reliable mesh. Similarly, in Case 2, the mesh was composed of 751,987 elements, with skewness also maintained under 0.8 and orthogonal quality exceeding 20%. These metrics demonstrate that the mesh for both configurations meets the required standards for CFD analysis, ensuring accurate and reliable simulation results for airflow and thermal performance in the classroom. Table 1 presents the spectrum of skewness mesh metrics, ranging from excellent to unacceptable, while Table 2 outlines the spectrum for orthogonal quality metrics, ranging from unacceptable to excellent [12][11][13].

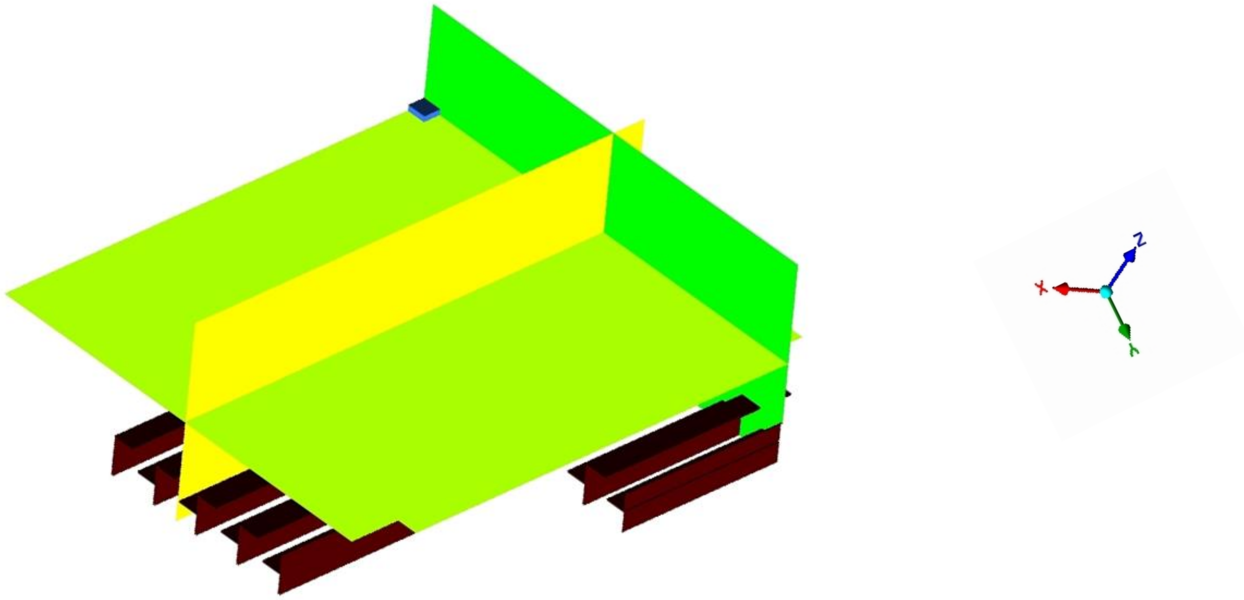


Figure 7:Three CFD contours (A, B and C) used to present the results of the simulations

3 Results and Discussion

Figure 7 illustrates three planes and two lines used for analyzing the CFD simulation results in the classroom environment. The planes are positioned on the lower half of the Z-axis, the Y-axis, and directly in front of the windows where the outdoor air interacts with the indoor space. These planes are utilized to generate CFD contours, providing detailed insights into airflow patterns, temperature distribution, and thermal comfort for both HVAC configurations.

Additionally, two reference lines are defined along the X-axis and Y-axis within the classroom model. These lines serve as key sections for comparing the performance of the two cases, enabling a clear evaluation of air velocity, temperature gradients, and the overall cooling effectiveness of each HVAC setup. This methodology ensures a comprehensive comparison of airflow behavior and energy efficiency between the configurations.

The contour results for the two cases provide insightful observations regarding the distribution of relative humidity within the lecture room. For Case 1, where the Free Stand Air Conditioner is placed near the large windows, the simulation demonstrates a localized impact on humidity distribution. This effect is most evident in the three contours shows in Figure 8 (A1, B1, and C1), which show a significant gradient in humidity levels. Areas closer to the air conditioning unit experience noticeably lower relative humidity, while regions farther away exhibit higher humidity levels. This uneven distribution indicates that the cooling effect in Case 1 is concentrated near the heat source, leaving other parts of the room inadequately cooled and less comfortable in terms of humidity levels. Such a pattern suggests that while the cooling system in this configuration effectively addresses localized heat, it struggles to achieve uniform conditions throughout space. In contrast, the results for Case 2, where a concealed air conditioning unit is installed near the ceiling, present a markedly different scenario. The contours shown in Figure 8 (A2, B2, and C2) reveal a more even distribution of humidity across the lecture room, highlighting improved air circulation and a balanced cooling effect. Also, it is important to note that the overall air in Case 2 appears warmer, as indicated by the relatively higher humidity levels. This observation implies that although the cooling distribution is superior, the system might not perform as efficiently in reducing the overall air temperature compared to Case 1.

These results highlight a trade-off between the two cases. While Case 1 offers localized cooling with significant humidity reduction near the air conditioning unit, it falls short in providing a uniform cooling effect throughout the room. Conversely, Case 2 excels in achieving even humidity distribution but results in higher air temperatures overall. These findings are essential in evaluating the effectiveness of each configuration and provide a foundation for determining the optimal setup to enhance thermal comfort in university classrooms. Further analysis incorporating thermal comfort indices such as PMV and PPD could help quantify the perceived comfort levels and guide the final recommendations.

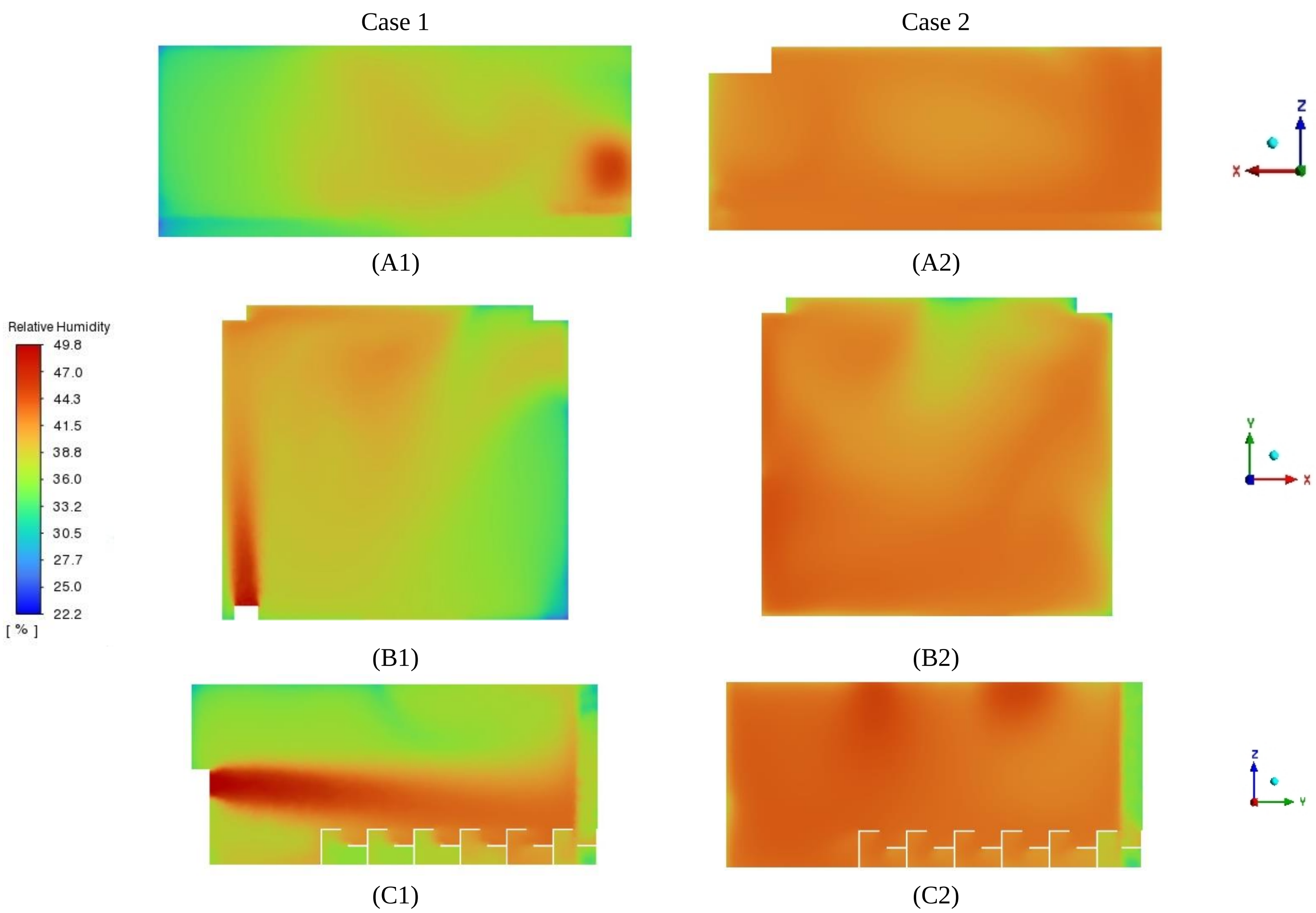


Figure 8:Relative humidity for the two studied cases along the three contours in lecture room

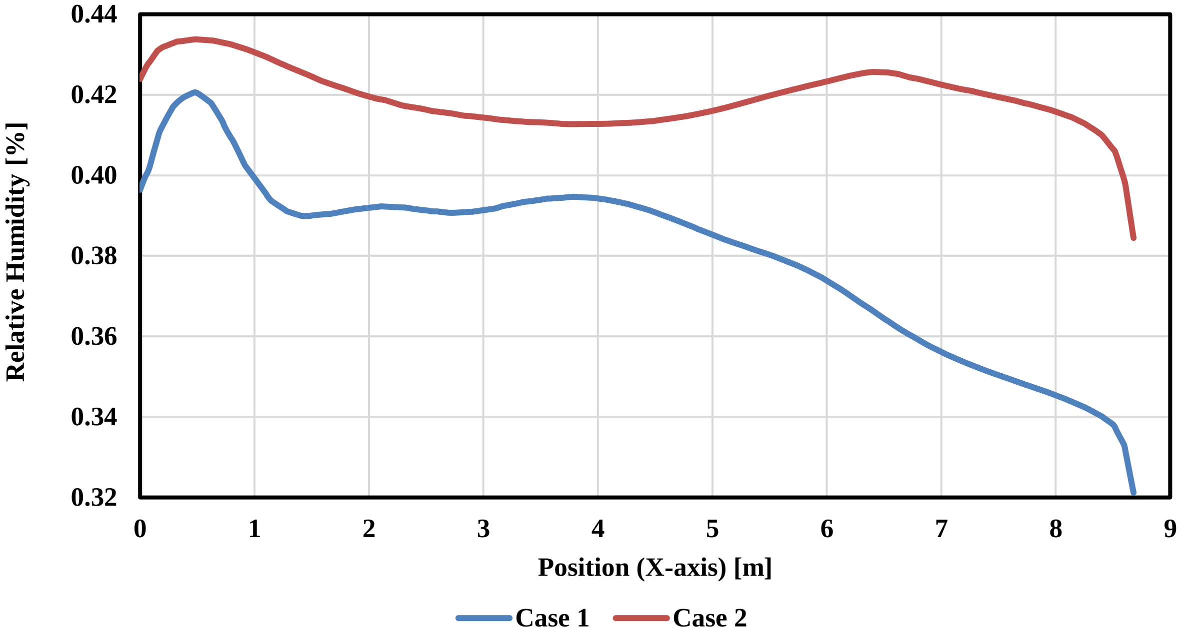


Figure 9: Relative humidity distribution along the X-axis of the classroom for Case 1 and Case 2.

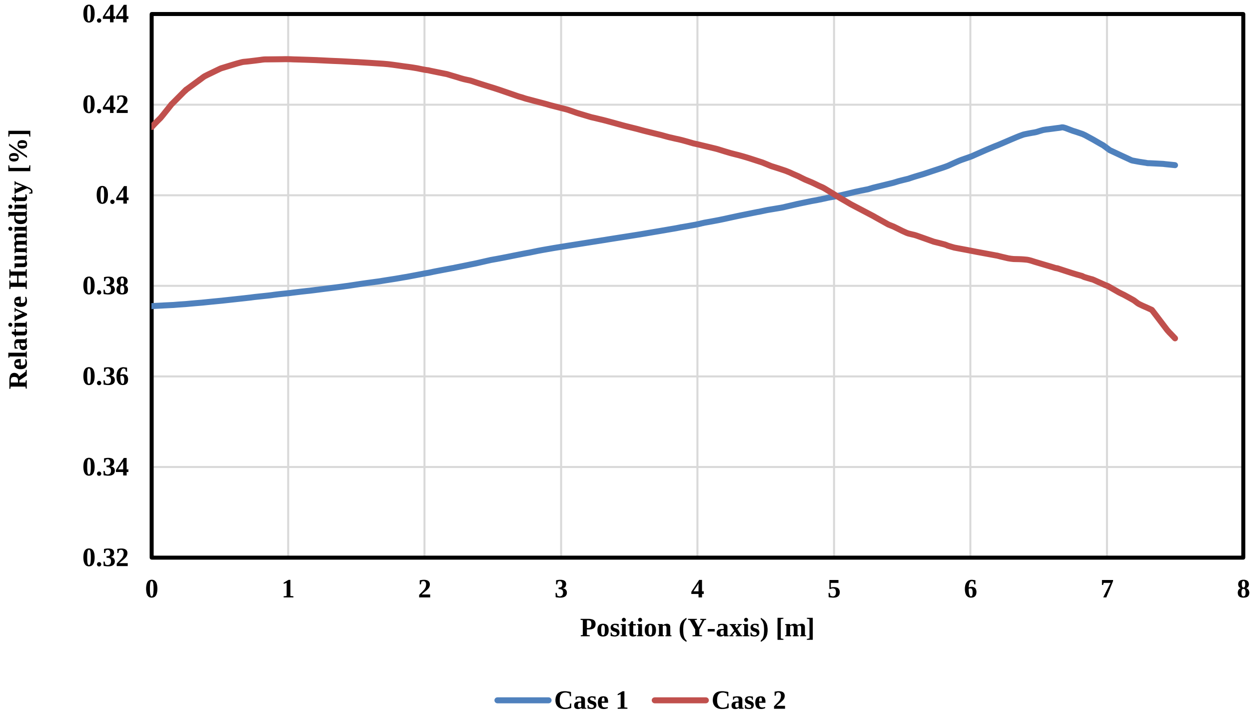


Figure 10: Relative humidity distribution along the Y-axis of the classroom for Case 1 and Case 2.

The presented graphs compare the relative humidity distribution within the classroom for two HVAC configurations, Case 1 and Case 2, along the X-axis and Y-axis. The first graph shown in Figure 9, representing the X-axis distribution, shows that Case 2 maintains a higher and more consistent relative humidity level (approximately 40–42%) across the length of the classroom. In contrast, Case 1 demonstrates a significant decline in relative humidity towards the rear of the room, highlighting its inability to provide uniform humidity distribution. The second graph shown in Figure 10, illustrating the Y-axis distribution, reveals that Case 2 achieves higher relative humidity at the front of the classroom, gradually decreasing towards the rear, while Case 1 exhibits the opposite trend, with relative humidity increasing as it moves towards the back. The intersection of the curves in the second graph underscores the inconsistent environmental control provided by Case 1 compared to the more balanced performance of Case 2. These findings clearly indicate that the ceiling-mounted HVAC system (Case 2) outperforms the free-standing air conditioner (Case 1) in achieving uniform relative humidity distribution, which is essential for maintaining optimal thermal comfort and air quality in educational spaces.

The temperature contour results for the two cases provide a detailed visualization of how each air conditioning configuration impacts the thermal distribution within the lecture room. In Case 1, where the Free Stand Air Conditioner is positioned near the heat source (large windows), the temperature contours shown in Figure 11 (A1, B1, and C1) show a strong localized cooling effect. The area immediately surrounding the air conditioning unit exhibits significantly lower temperatures, as depicted by the blue regions near the unit. However, this cooling effect diminishes as the distance from the air conditioner increases, resulting in uneven temperature distribution throughout the room. The presence of red and orange zones near the windows further highlights the limitations of this configuration in uniformly mitigating the heat generated by direct sunlight.

In Case 2, the concealed air conditioning unit placed near the ceiling offers a more balanced temperature distribution across the room, as evident from the contours shown in Figure 11 (A2, B2, and C2). The cooling effect is more evenly spread, with fewer hot zones and a relatively consistent temperature throughout space. The uniformity of the temperature in this case suggests improved air circulation due to the placement of the air conditioning unit, allowing cool air to diffuse more effectively across the room. However, the temperature levels in Case 2 are slightly higher overall compared to Case 1, which might reduce its cooling efficiency despite the better distribution.

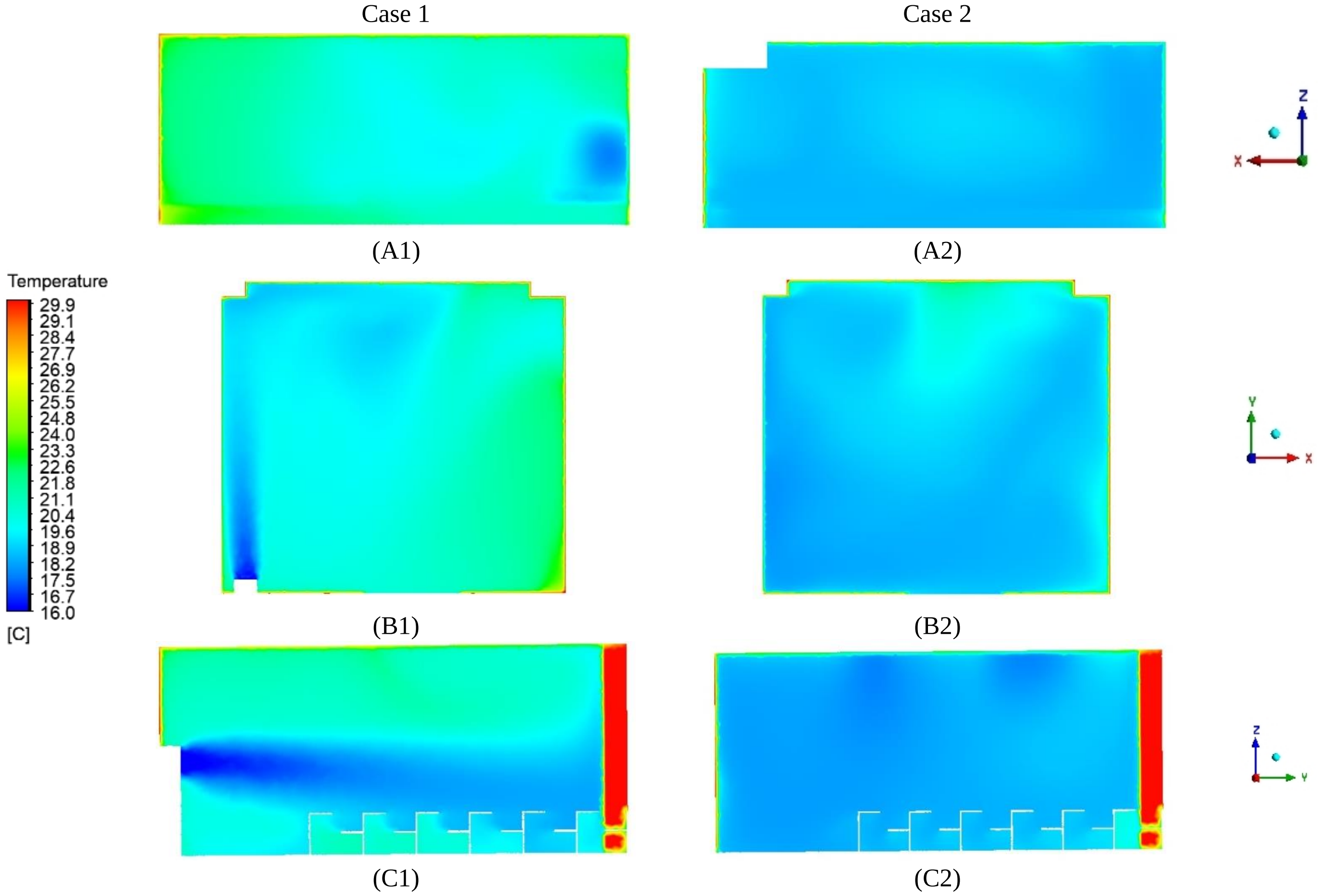


Figure 11:Temperature for the two studied cases along the three contours in lecture room

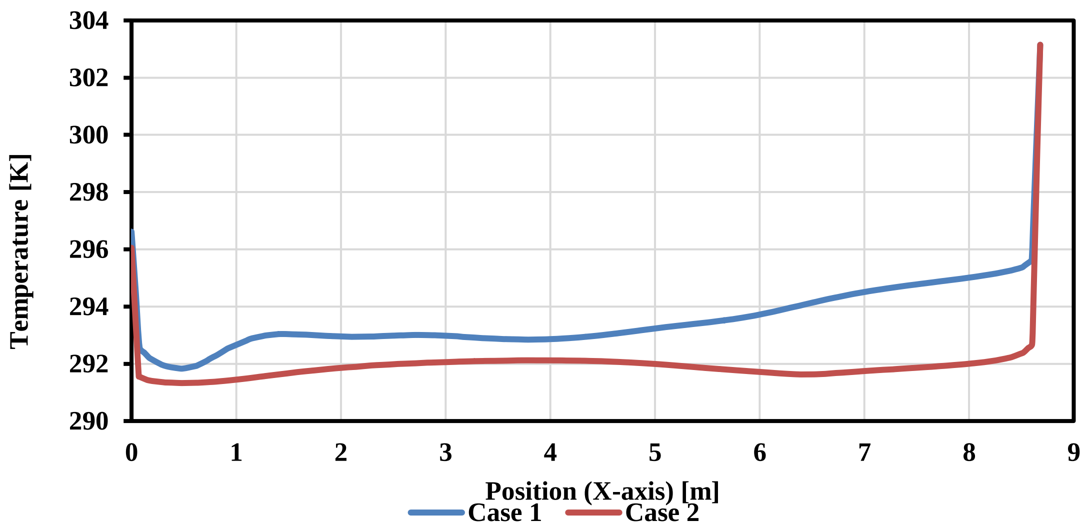


Figure 12: Temperature distribution along the X-axis of the classroom for Case 1 and Case 2

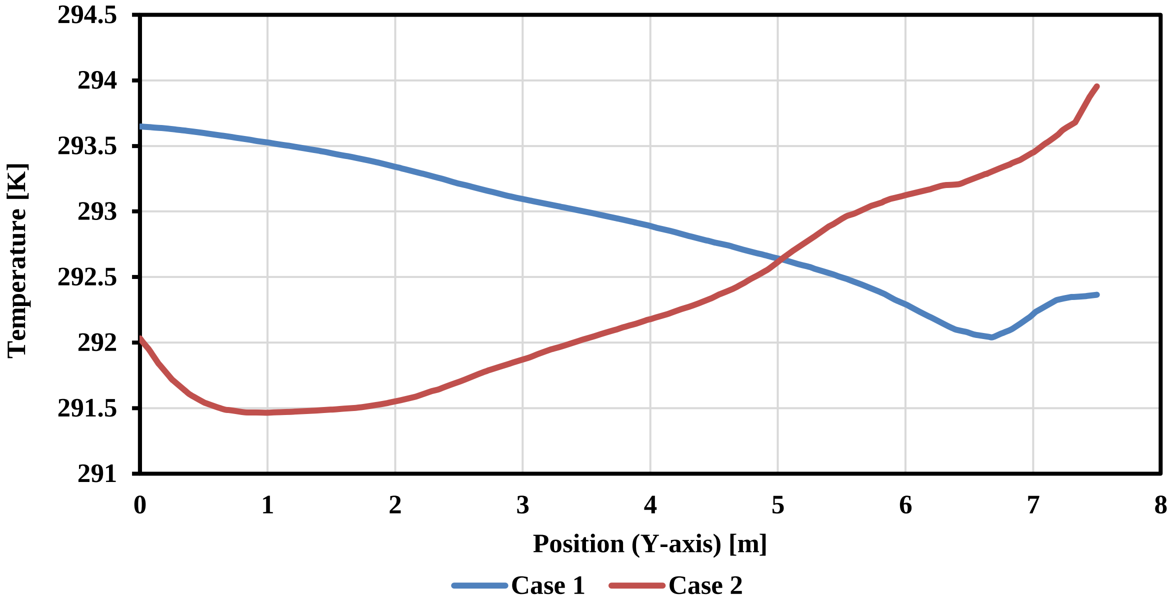


Figure 13: Temperature distribution along the Y-axis of the classroom for Case 1 and Case 2.

These results highlight the difference between the two configurations. Case 1 is effective at providing localized cooling but fails to achieve uniform thermal conditions, potentially leading to thermal discomfort in areas farther from the air conditioning unit. Conversely, Case 2 offers a more consistent temperature distribution, which is beneficial for overall thermal comfort, but it may lack the intensity of cooling required to combat higher heat levels.

The temperature distribution graphs along the X-axis and Y-axis highlight the differences in thermal performance between Case 1 (free-standing air conditioner) and Case 2 (ceiling-mounted HVAC system). The X-axis graph shown in Figure 12 shows that Case 1 results in higher temperature variation, with a significant increase in temperature towards the rear of the classroom. In contrast, Case 2 maintains a more consistent temperature profile across the X-axis, with only minor fluctuations. This indicates that Case 2 provides better thermal uniformity, reducing discomfort caused by localized heating or cooling.

The Y-axis graph shown in Figure 13 further emphasizes these differences. In Case 1, the temperature decreases towards the rear of the room, with a noticeable gradient across the Y-axis. Conversely, Case 2 achieves a more stable temperature distribution, with only a slight increase towards the rear. The intersection of the temperature curves for the two cases highlights the more balanced thermal environment achieved by Case 2. These findings demonstrate the superior performance of the ceiling-mounted HVAC system in maintaining consistent and comfortable thermal conditions throughout the classroom, contributing to improved occupant comfort and learning conditions.

The velocity contours for the two cases present a vivid narrative of how airflow behaves under each air conditioning setup, shedding light on the distribution of air movement within the lecture room. In Case 1, with the Free Stand Air Conditioner located near the heat source, the velocity contours shown in Figure 14 (A1, B1, and C1) reveal a concentrated region of high airspeed near the AC unit. This localized burst of airflow is evident in the bright red and orange zones near the air conditioner. However, the energy of the airflow dissipates quickly as it moves away from the unit, resulting in an uneven distribution of air velocity. The rest of the room, particularly the corners and regions far from the AC, remains largely stagnant, as indicated by the dominance of blue shades. This pattern suggests that while the cooling device is powerful in its immediate vicinity, its influence diminishes sharply across the room, potentially leaving some areas inadequately ventilated. Although in Case 2, featuring a concealed air conditioning system mounted near the ceiling, offers a markedly different airflow profile, as depicted in the velocity contours shown in Figure 14 (A2, B2, and C2). The airflow in this setup is more diffuse, with moderate velocities distributed more evenly throughout the space. While there are no extreme high-speed zones like those seen in Case 1, the air movement covers a broader area, maintaining a consistent flow pattern. This even distribution ensures that no part of the room is left completely stagnant, contributing to better air circulation overall. The placement of the air conditioning unit near the ceiling appears to enhance its ability to spread air uniformly, leveraging the downward flow of cooler air. This could be particularly advantageous in maintaining a balanced thermal environment, where every occupant experiences similar conditions.

The implications of these velocity contours go beyond airflow alone. The effectiveness of air movement has a direct impact on thermal comfort indices such as PMV and PPD, as well as on the perceived freshness and air quality within the space. By combining this analysis with insights from temperature and humidity distributions, the study provides a holistic understanding of how each configuration affects the overall environment. These observations lay the groundwork for informed decision-making when optimizing air conditioning systems for similar lecture rooms.

The range of differences in airflow velocities at the windows and doors for Case 1 and Case 2 are observed to be nearly equivalent. This result can be attributed to the placement and configuration of the HVAC components. Specifically, the positioning of the inlets and outlets directly influences the localized airflow patterns, resulting in a similar range of velocity variations despite the different system setups. The presence of high airflow near the sources and a gradual decrease as the distance increases is consistent across both cases due to the fundamental principles of momentum conservation and diffusion in enclosed spaces

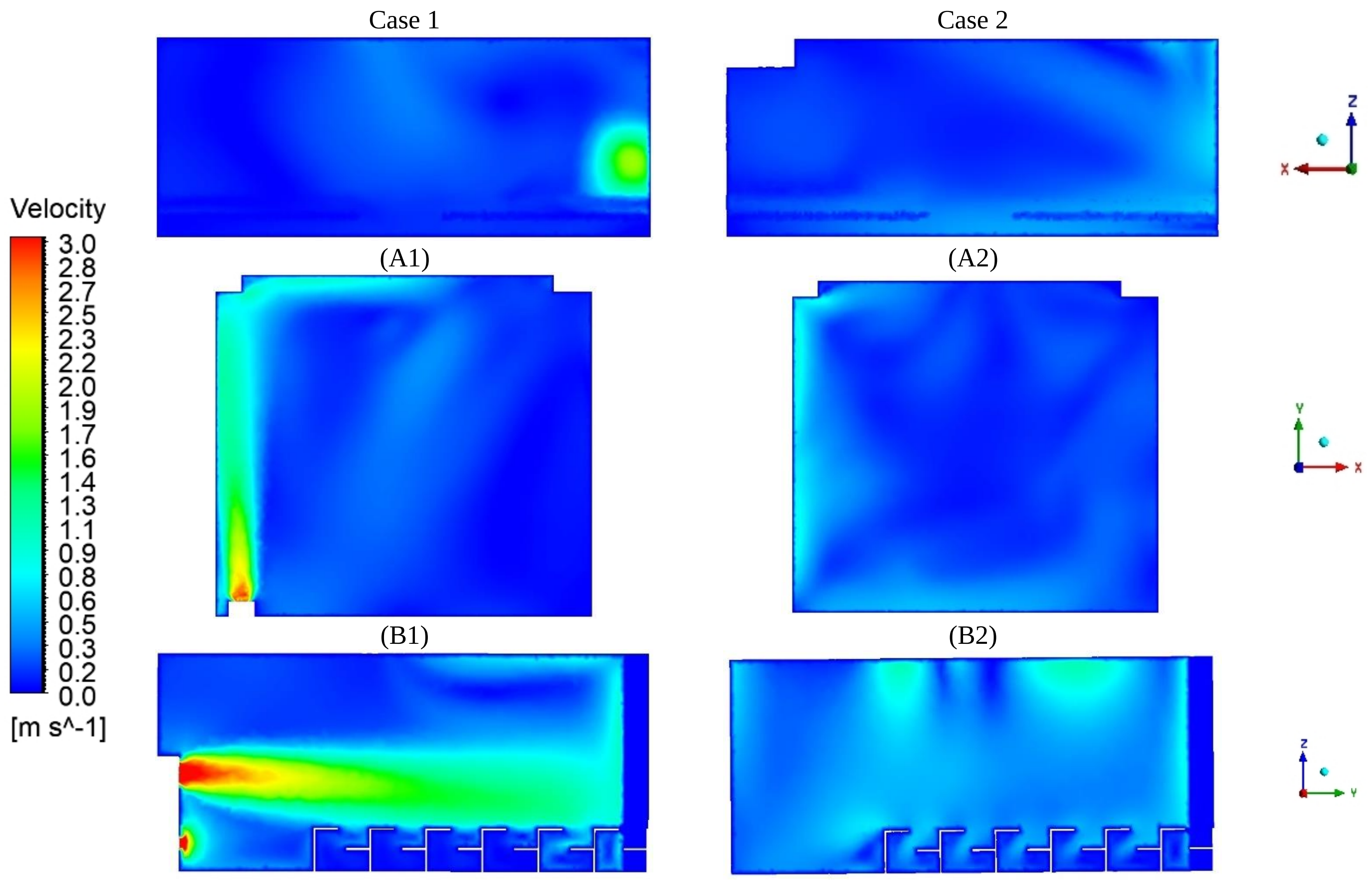


Figure 14:Flow velocity for the two studied cases along the three contours in lecture room

The velocity distribution graphs along the X-axis and Y-axis illustrate the airflow characteristics of the two HVAC configurations, Case 1 and Case 2. The X-axis graph shown in Figure 15 reveals that Case 1 generates significantly higher air velocity near the inlet, peaking at approximately 1.2 m/s, but this quickly decreases as airflow progresses through the room. This results in uneven airflow distribution, with some areas experiencing stagnant air. In contrast, Case 2 maintains a more consistent airflow velocity, ranging between 0.2 and 0.4 m/s across the X-axis, indicating better air circulation and mixing throughout the classroom. The Y-axis graph shown in Figure 16 provides further evidence of these differences. Case 1 exhibits a sharp increase in velocity near the inlet, followed by a steady decline, leading to poor air movement towards the back of the classroom. Conversely, Case 2 demonstrates a smoother and more uniform velocity distribution, maintaining airflow levels between 0.1 and 0.3 m/s across the room's height. This consistency ensures enhanced air mixing and better occupant comfort. These results highlight the superiority of the ceiling-mounted HVAC system (Case 2) in achieving balanced airflow distribution, addressing the localized cooling and stagnation issues observed with the free-standing air conditioner (Case 1).

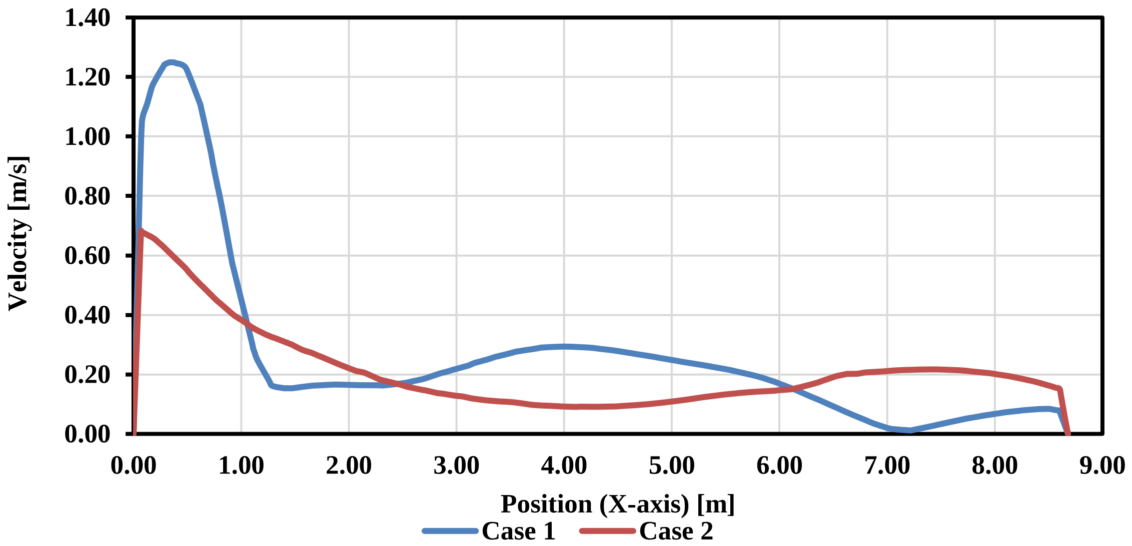


Figure 15: Velocity distribution along the X-axis of the classroom for Case 1 and Case 2.

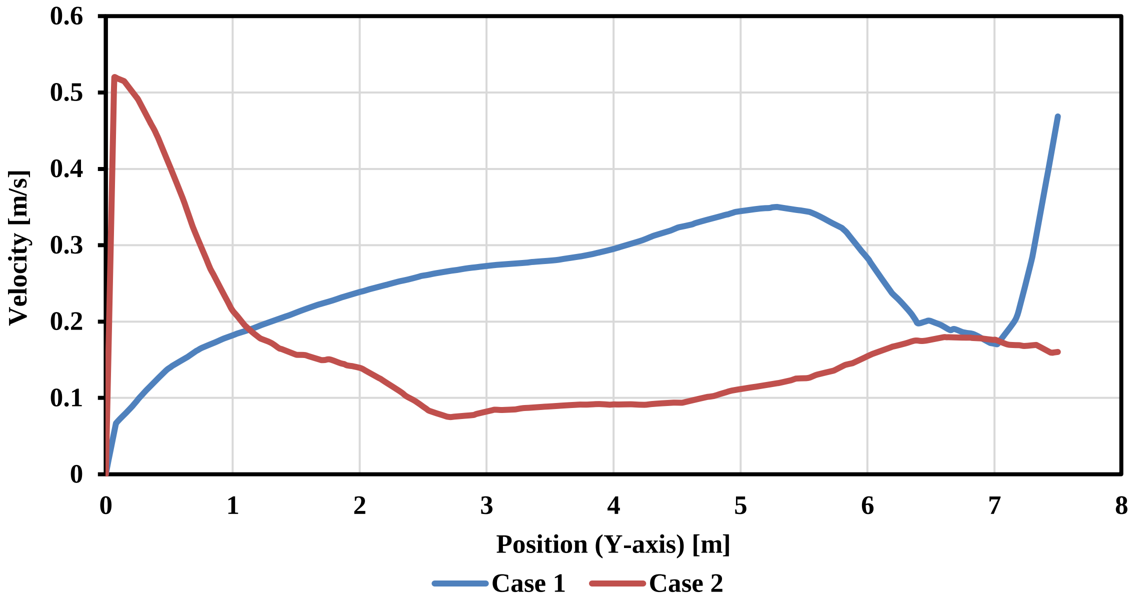


Figure 16: Velocity distribution along the Y-axis of the classroom for Case 1 and Case 2.

The PMV (Predicted Mean Vote) contour plots shown in Figure 17 compare the thermal comfort levels for the two HVAC configurations, Case 1 and Case 2, along three orientations within the classroom: horizontal (A1 and A2), vertical (B1 and B2), and sectional (C1 and C2). These contours highlight the spatial variations in thermal comfort as influenced by each HVAC system.In the horizontal plane (A1 and A2), Case 1 shows significant localized discomfort, particularly near the air conditioning unit, where PMV values exceed 1.5, indicating overheating. In contrast, Case 2 exhibits a more uniform PMV distribution with values closer to neutral (0 to ±0.5), signifying better thermal comfort throughout the room.In the vertical plane (B1 and B2), Case 1 demonstrates uneven PMV values, with areas near the floor and ceiling showing significant deviations from neutral comfort levels. On the other hand, Case 2 maintains consistent PMV values across the vertical axis, with minimal variations, highlighting its effectiveness in distributing conditioned air evenly across different room heights

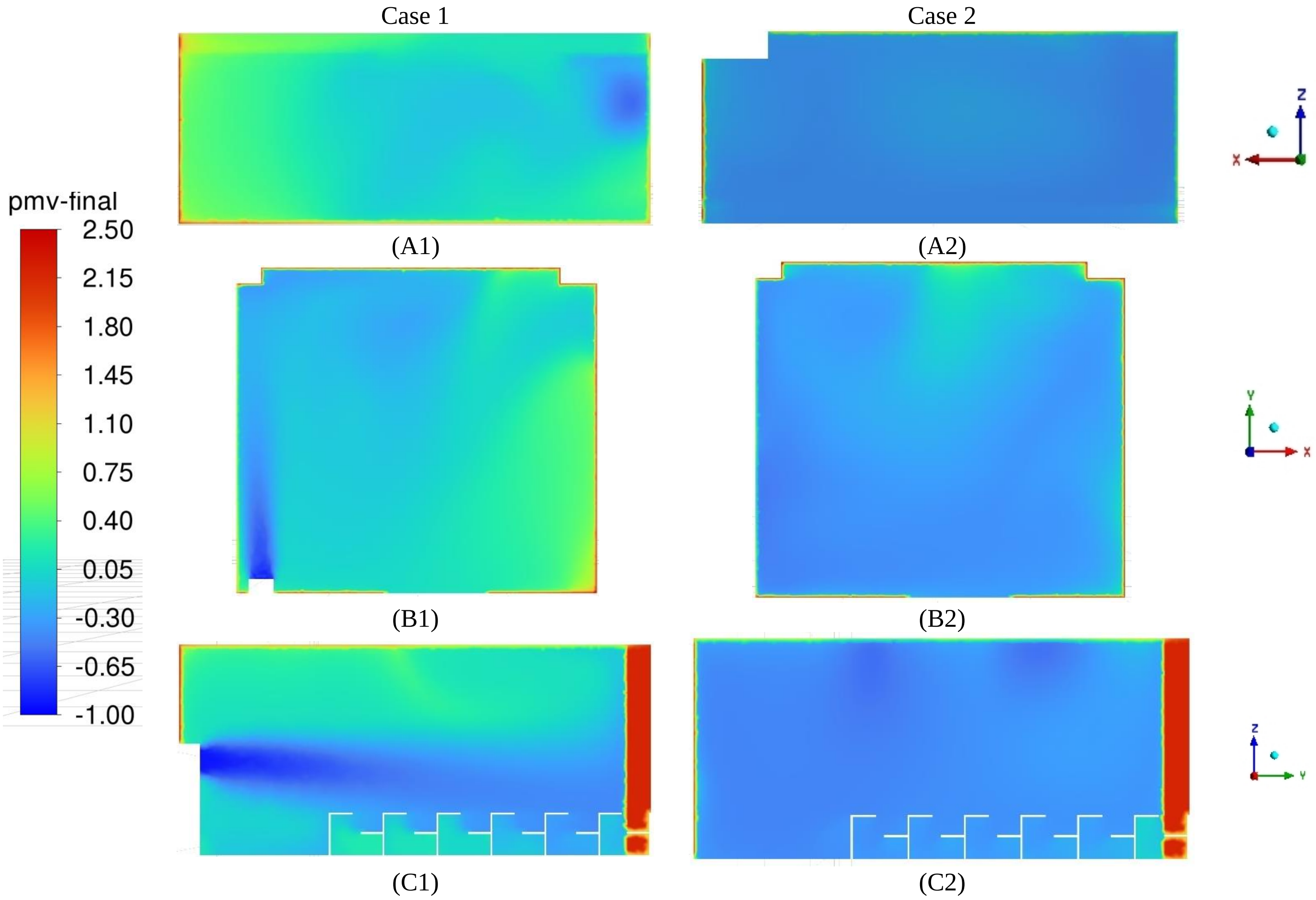


Figure 17: PMV contours for the two studied cases along the three contours in lecture room

The sectional contours (C1 and C2) shown in Figure 17 further underscore the disparities. In Case 1, PMV values near the air outlet spike, creating discomfort zones, while the rear sections remain cooler and closer to -1. This uneven distribution reflects poor airflow mixing. Conversely, Case 2 provides a balanced PMV profile across the entire sectional plane, avoiding extreme hot or cold zones and ensuring thermal comfort for all occupants. These PMV contours clearly indicate that the concealed ceiling-mounted HVAC system (Case 2) significantly outperforms the free-standing air conditioner (Case 1) in providing uniform thermal comfort, making it a better choice for ensuring an optimal indoor environment in lecture rooms.

The PPD (Predicted Percentage of Dissatisfied) contour plots shown in Figure 18 evaluate the thermal comfort performance of the two HVAC configurations, Case 1 and Case 2, across three orientations in the classroom: horizontal (A1 and A2), vertical (B1 and B2), and sectional (C1 and C2). These contours illustrate the percentage of occupants likely to feel thermal discomfort in different areas of the classroom. In the horizontal plane (A1 and A2), Case 1 exhibits higher PPD values in localized regions near the air conditioner and windows, with values reaching above 25%, indicating significant discomfort for a portion of the occupants. Conversely, Case 2 demonstrates a uniform PPD distribution with values below 10% across most areas, reflecting a thermally comfortable environment. In the vertical plane (B1 and B2), Case 1 shows noticeable variations in PPD values, with the areas near the floor and ceiling experiencing discomfort levels exceeding 20%, signifying poor vertical airflow distribution. In contrast, Case 2 maintains a consistent PPD distribution with values remaining below 15% throughout the vertical section, showcasing its ability to deliver even air circulation and improve occupant comfort.

The sectional contours (C1 and C2) further emphasize the contrast between the two cases. In Case 1, PPD values spike near the air outlet, exceeding 35%, while the rear section shows a more comfortable range. However, this uneven distribution highlights poor airflow mixing. Case 2, on the other hand, achieves balanced PPD values across the entire section, maintaining values below 15% and ensuring thermal comfort for the majority of the occupants. Overall, the PPD contours affirm the superiority of the concealed ceiling-mounted HVAC system (Case 2) in creating a thermally comfortable environment with minimal dissatisfaction, significantly outperforming the free-standing air conditioner (Case 1).

The performance differences between the free-standing air conditioner (Case 1) and the concealed ceiling-mounted system (Case 2) are rooted in their structural configurations. Case 1's single inlet and outlet design focuses the airflow near the immediate vicinity of the AC unit, leading to localized cooling but inadequate circulation in the far corners of the room. Conversely, Case 2's distributed inlet and outlet setup ensures a more uniform spread of air, enhancing overall circulation and reducing temperature gradients. This highlights the critical role of HVAC design in achieving consistent thermal comfort.

To further illustrate, the placement of the concealed system's outlets near the ceiling leverages the natural tendency of cool air to sink, which enhances the diffusion of conditioned air throughout the space. Meanwhile, the free-standing system, despite its high localized velocity, lacks the architectural advantage to uniformly distribute airflow across the room's volume.

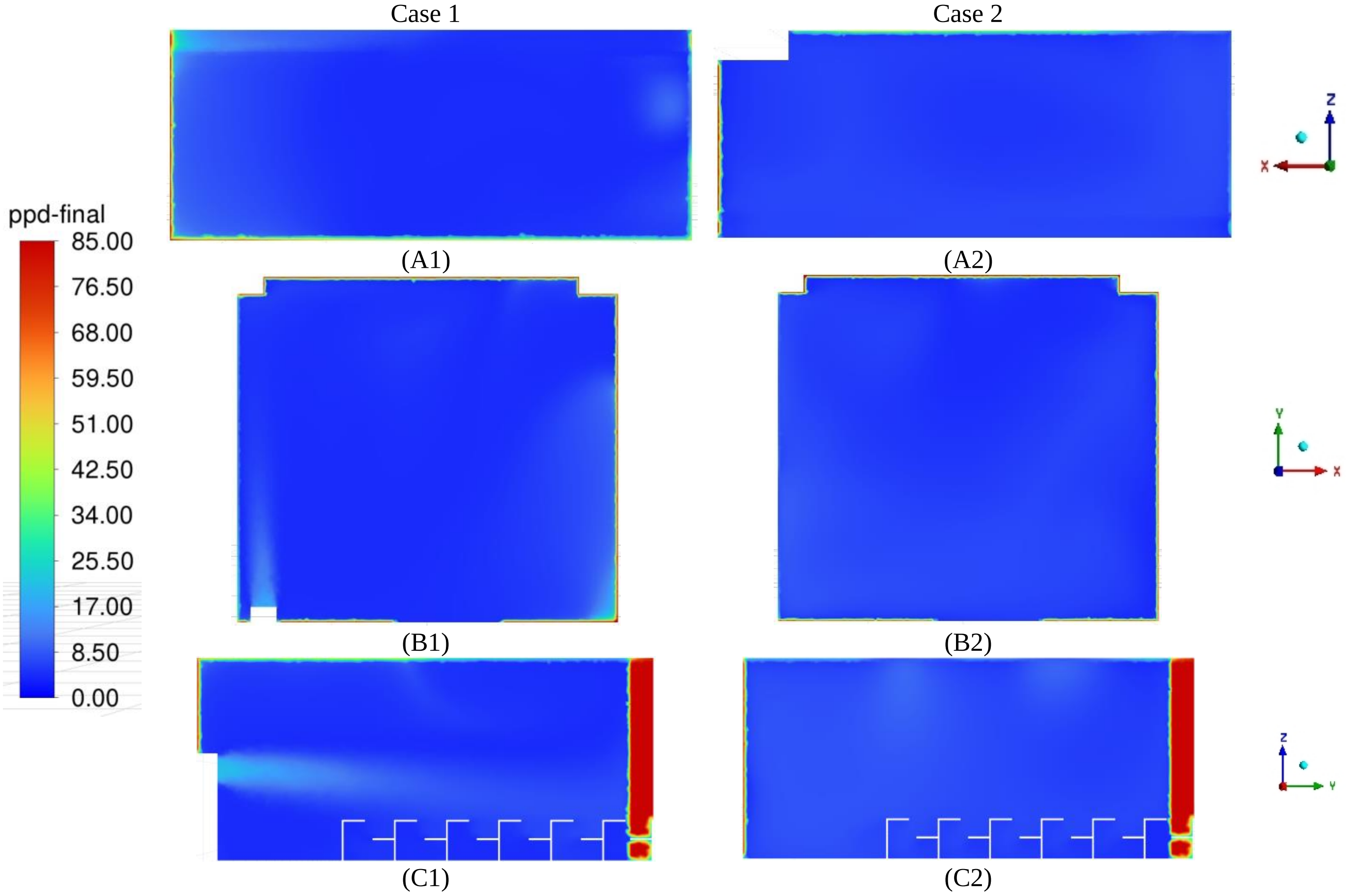


Figure 18: PPD contours for the two studied cases along the three contours in lecture room

4 Limitations

Limitations of the study include simplifications made in the simulation model to reduce computational complexity, as well as potential discrepancies between simulated and real-world conditions. Additionally, the study focuses exclusively on thermal comfort and does not address other aspects of indoor environmental quality. Through this numerical simulation-based methodology, this study aims to provide valuable insights into the factors affecting thermal comfort within university classrooms, informing the design and operation of educational spaces to enhance occupants' comfort and well-being.

Conclusions

This study assessed the thermal performance and airflow distribution of two HVAC configurations in a university classroom using CFD simulations. The results highlighted key differences in the effectiveness of each configuration, quantified using temperature distribution and air velocity data.

1. **Case 1**: The free-standing air conditioner, with a single inlet (550 mm × 500 mm) and outlet (550 mm × 250 mm), positioned near windows exposed to sunlight, resulted in uneven cooling. The airflow distribution created noticeable temperature gradients, with a maximum temperature difference of **6–8°C** between the front and rear sections of the classroom. Air velocity near the windows was higher (**0.5–0.7 m/s**) compared to other areas, indicating localized cooling with poor air mixing.
2. **Case 2**: The concealed ceiling-mounted air conditioning system, equipped with two inlets (1200 mm × 200 mm each) and two outlets (600 mm × 600 mm each), achieved better performance. The maximum temperature difference within the classroom was reduced to **2–3°C**, ensuring more uniform thermal comfort. Air velocity distribution was more balanced, with values ranging between **0.3–0.5 m/s** throughout the room, reflecting enhanced airflow circulation.

The CFD simulations converged with high accuracy (1 × 10^(-3)), confirming the reliability of the results. The analysis indicates that Case 2 offers a significantly improved solution, providing consistent cooling and better thermal comfort for classroom occupants. Future studies may integrate energy efficiency metrics and experimental validation to further optimize HVAC configurations.

While the current study effectively highlights the thermal and airflow performance of the two HVAC configurations, the findings could be significantly enriched by exploring alternative simulation models. For instance, employing different turbulence models, such as Large Eddy Simulation (LES), could provide a more granular understanding of airflow dynamics. Additionally, refining mesh configurations or incorporating energy efficiency metrics into the analysis could further validate the results. Future work may also involve experimental validation to align the simulated data with real-world measurements, offering comprehensive insights into the interaction between airflow patterns and energy consumption.

Such advancements would not only strengthen the conclusions drawn but also provide actionable guidelines for optimizing HVAC designs in educational spaces. Furthermore, incorporating transient simulations to account for occupant behavior and variable thermal loads could present a more dynamic and realistic evaluation of HVAC system performance.

Declarations

Availability of data and materials

The authors have not used any data in our study.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

All authors contributed extensively to the work presented in this paper. AH led the entire process of this study. All authors read and approved of the final manuscript.

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