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Design Simulation and Data Analysis of an Air Handling System in Wards and COVID-19 Enclosure Using Computational Fluid Dynamics

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Abstract

Air Handling Units (AHUs) play a critical role in mechanical systems, conditioning and circulating air as part of heating, ventilating, and air conditioning (HVAC) systems. These systems are essential in hospital settings to ensure comfort and maintain high indoor air quality for patients, staff, and visitors. The design of HVAC systems in hospitals must meet stringent requirements, including optimal temperature distribution, thermal comfort, and effective contaminant removal. This study evaluates the indoor air quality (IAQ) of the AHU design at the Northern Mindanao Medical Center Hospital using Computational Fluid Dynamics software. The HVAC system was modeled and simulated in SOLIDWORKS, focusing on thermal comfort parameters such as airflow velocity (0.15–0.25 m/s), temperature (21–23.5 °C), and relative humidity (40–50%). The simulation results demonstrated compliance with ASHRAE 55 and ISO 7730 standards, with Predicted Mean Vote (PMV) values between –0.5 and +0.5 and Predicted Percentage of Dissatisfied (PPD) below 20%. Contaminant Removal Effectiveness (CRE) values exceeded 1.0 across all rooms, while the Local Air Quality Index (LAQI) ranged from 1.1 to 1.9. These findings underscore the efficacy of the designed AHU in ensuring a comfortable and safe indoor environment in the hospital.

***Keywords**:* AHU, CFD simulation, HVAC system, hospital, thermal comfort

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1. Introduction

Heating, ventilation, and air conditioning (HVAC) systems are essential mechanical infrastructure that ensure optimal indoor air quality and thermal comfort by collecting outdoor and indoor air, removing dust and other particles, adjusting temperature and humidity, and supplying conditioned air to rooms through a network of ducts. Central to HVAC systems is the air-handling unit (AHU), often regarded as the heart of central air conditioning (Goldanlou *et al.*, 2020). The primary role of the AHU is to condition and circulate air, thereby providing a comfortable, high-quality environment for patients, staff, and visitors in hospital settings.

Hospitals are environments where the presence of viruses, bacteria, and other microorganisms is a persistent concern (Cruz-López *et al.*, 2023). Effective HVAC systems are crucial for preventing the spread of these pathogens and isolating them within specific areas. A study by the University of Cordoba underscores the importance of robust ventilation systems in significantly reducing the transmission of microorganisms (Berlanga *et al.*, 2018). To achieve this, healthcare facilities must introduce substantial volumes of fresh air to ventilate areas effectively and remove pollutants generated within rooms. Ventilation rates in such settings are quantified as air changes per hour (ACH), which measures how often indoor air is replaced with outdoor or conditioned air. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers recommends a minimum of six air exchanges per hour in patient rooms and twelve in operating rooms to ensure adequate ventilation and contaminant removal (Contrada *et al.*, 2022).

In addition to pathogen control, ventilation systems are critical for maintaining thermal comfort by regulating indoor air temperature and humidity. Globally recognized standards such as ASHRAE 55 and ISO 7730 define thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment" (Özbey *et al.*, 2025). Achieving thermal comfort is especially vital in healthcare settings, where the indoor environment directly affects the well-being and performance of patients and staff. Designing HVAC systems for healthcare facilities requires strict adherence to specifications to mitigate airborne disease transmission while ensuring a comfortable, conducive environment for healing and care.

Simulation tools, particularly Computational Fluid Dynamics software, are invaluable in the early stages of HVAC system design. These tools enable engineers to model and analyze airflow patterns, temperature distributions, and contaminant removal, supporting more cost-effective and efficient design decisions (Zhao *et al*., 2021; Zomorodian *et al*., 2016; Rupp *et al*., 2015). By simulating the HVAC system, engineers can predict performance, identify potential issues, and optimize configurations before physical implementation.

Previous CFD-based studies on hospital ventilation have primarily focused on isolated parameters such as airflow or contaminant removal, with limited integration of thermal comfort indices and IAQ metrics. This study addresses these gaps by simultaneously evaluating airflow velocity, temperature, humidity, predictive mean vote (PMV), predicted percentage of dissatisfied (PPD), contaminant removal effectiveness (CRE), and local air quality index (LAQI) in hospital wards and COVID-19 enclosures. The novelty lies in applying CFD to a hospital-specific AHU design and benchmarking it against international standards. In particular, Le *et al*. (2022) on airborne infection isolation rooms highlight the relevance of CFD in optimizing hospital ventilation systems, and their findings are used as a comparative reference in this study.

2. Methodology

2.1 Research Design

This study used a quantitative, simulation-based research design with Computational Fluid Dynamics (CFD) to evaluate airflow, thermal comfort, and contaminant removal performance of the AHU system in the 6th-floor expansion ward of Northern Mindanao Medical Center.

2.2 Data Sources and Geometry Modeling

Actual architectural floor plans and HVAC design specifications from the hospital engineering department were used. The 3D geometry of wards, ducts, supply diffusers, and return vents was modeled in SOLIDWORKS.

2.3 Simulation Inputs and Boundary Conditions

Computational Fluid Dynamics (CFD) simulation is an important tool in engineering and science for analyzing and predicting the behavior of fluids, such as air and water, in various physical systems (Chen *et al*., 2023; Widiastuti *et al*., 2020). It plays a crucial role in the design and optimization of ventilation systems, providing insights into airflow patterns, temperature control, contaminant removal, natural ventilation, and fire safety. Figure 1 shows a CFD simulation of the wards at Northern Mindanao Medical Center Hospital using the SOLIDWORKS application, illustrating the working CFD simulation of both zones 1 and 2 of NMMC's new building. The room dimensions are approximately 3.0 m by 4.0 m. The velocity is set below 2000 fpm (10.16 m/s) to prevent the ducting system from vibrating and producing noise that is uncomfortable for occupants (He *et al*., 2022).

The Computational Fluid Dynamics (CFD) simulations were executed using a steady-state, pressure-based solver with the k–ε turbulence model, which is widely adopted for indoor airflow analysis due to its robustness and computational efficiency. The governing equations for mass, momentum, and energy were solved using the SIMPLE algorithm for pressure–velocity coupling. A second-order upwind scheme was applied to improve numerical accuracy in regions of high velocity gradients. Mesh independence was verified by refining the grid from coarse to fine resolutions until variations in average velocity and temperature were below 2%, confirming that the solution was insensitive to further refinement. Convergence was achieved when all residuals fell below 10^{-4}, ensuring numerical stability and physical consistency of the results.

To prevent numerical diffusion and ensure realistic representation of airflow, the computational domain was discretized using a hybrid mesh composed of hexahedral and tetrahedral elements. Boundary conditions included an inlet velocity below 10.16 m/s (2000 fpm), outlet pressure at atmospheric level, and thermal loads derived from hospital occupancy and equipment heat generation. Air properties were assumed to be incompressible and Newtonian, with constant density and viscosity at 25 °C. The simulations were conducted under steady-state conditions, neglecting transient fluctuations, as the primary objective was to evaluate equilibrium airflow and contaminant removal performance. These parameters collectively guarantee that the CFD model accurately represents the physical behavior of the hospital's air-handling system and complies with ASHRAE 55 and ISO 7730 standards.

The CFD simulation was conducted using SOLIDWORKS Flow Simulation. Boundary conditions included an inlet velocity below 10.16 m/s (2000 fpm) to prevent duct vibration, an outlet pressure at atmospheric level, and thermal loads based on hospital occupancy. Data sources included architectural floor plans of the NMMC expansion building and ASHRAE 55/170 standards. Parameters analyzed were airflow velocity, temperature, relative humidity, PMV, PPD, CRE, and LAQI. Validation was performed by comparing simulation outputs with published CFD studies (Le *et al*., 2022; Alkhalaf *et al*., 2023) and by ensuring compliance with ASHRAE and ISO thresholds. This structured approach enhances reproducibility and transparency.

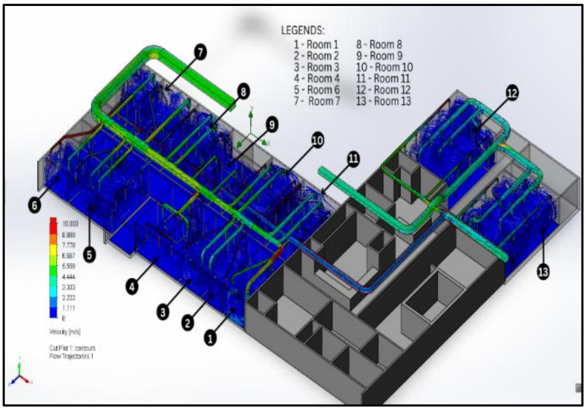


Figure 1. Simulation of the designed AHU

2.3.1 Contaminant Representation in CFD

Airborne contaminants were modeled in the CFD simulations as passive scalar species, which allowed their transport to be solved alongside the momentum and energy equations. This approach assumes that contaminants behave as tracers carried by airflow, without influencing the flow field itself. Source concentrations were introduced at patient breathing zones and watcher locations to replicate realistic emission points. The scalar transport equation was then used to calculate contaminant dispersion, dilution, and removal through exhaust outlets. This methodology provided the basis for computing Contaminant Removal Effectiveness (CRE) and the Local Air Quality Index (LAQI), both of which quantify the efficiency of the ventilation system in reducing exposure to airborne pollutants.

To ensure accuracy, contaminant boundary conditions were defined with uniform emission rates consistent with published hospital ventilation studies. Exhaust vents were treated as sinks, removing contaminants at rates proportional to airflow. By coupling contaminant transport with airflow velocity and thermal fields, the simulation captured the interaction between ventilation design and infection-control performance. This representation allowed the study to evaluate not only airflow distribution but also the system's ability to dilute and remove pathogens, thereby supporting infection-control strategies in wards and COVID-19 enclosures. The results demonstrated CRE values consistently greater than 1.0 and LAQI values between 1.1 and 1.9, confirming that the modeled AHU design exceeded baseline contaminant removal requirements.

2.4 Study Variables

This study evaluates the performance of the hospital Air Handling Unit (AHU) system using key environmental and ventilation variables that directly affect indoor air quality and occupant comfort. The primary variables include air velocity (m/s) to assess airflow distribution and compliance with draft limits; air temperature (°C) and relative humidity (%) to determine thermal comfort; Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) to quantify occupant thermal sensation and comfort acceptability according to international standards; and Contaminant Removal Effectiveness (CRE) and the Local Air Quality Index (LAQI) to evaluate ventilation efficiency and airborne contaminant removal performance. These variables were analyzed at multiple room locations and heights to provide a comprehensive assessment of airflow behavior, thermal stratification, and infection-control effectiveness within the hospital ward and COVID-19 enclosure.

The hospital wards and COVID-19 enclosures were grouped based on identical geometric layouts and ventilation configurations. Rooms with similar floor dimensions, diffuser placements, and return vent arrangements were categorized together to streamline the simulation process. This grouping ensured that representative airflow and contaminant removal patterns could be analyzed without duplicating computational effort across rooms with equivalent designs. For example, Rooms 1, 2, and 3 shared the same geometry and diffuser layout, allowing a single representative simulation to capture the airflow behavior applicable to all three.

2.4.1 Flow Velocity

Airflow velocity measurement provides a quantitative assessment of the AHU's performance. It is essential for maintaining occupant comfort and plays a critical role in controlling indoor air quality (Zhou *et al*., 2021). The AHU's ability to supply and distribute fresh, filtered air depends on proper airflow velocities. By measuring velocity, you can assess whether the AHU is providing adequate air changes per hour, which is crucial for diluting and removing contaminants. Insufficient airflow can lead to poor air distribution, allowing pollutants to accumulate in certain areas while leaving others under-ventilated. On the other hand, excessive airflow velocities can cause turbulent conditions that may stir up particulate matter or create uncomfortable drafts.

2.4.2 Temperature and Humidity Measurements

Temperature and humidity measurements are vital for assessing the effectiveness of ventilation systems. In CFD models, temperature measurements can pinpoint uncomfortable spots in space and improve how well the ventilation system functions (Kalmár *et al.*, 2022). For instance, if temperature data indicate that some portions of the room are either too hot or too cold, modifications to the ventilation system can be made to optimize the temperature distribution. Furthermore, temperature measurements can be used to calculate the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) to evaluate thermal comfort levels. Thermal measurements are also used in various studies conducted by different researchers to evaluate the thermal comfort of a room.

According to the ASHRAE Handbook, temperature and humidity are conditions that can inhibit or promote the growth of bacteria and activate or deactivate viruses. Therefore, proper control and monitoring of these conditions are highly relevant in healthcare facilities. According to Ibrahim *et al*. (2024), ASHRAE Standard 170-2017, Ventilation of Healthcare Facilities, identifies the level of humidity in a healthcare facility as an area of active research. This means that there is no established standard from ASHRAE, and it remains a subject of research interest. However, Guarnieri *et al.* (2023) demonstrated that the risk increases when the relative humidity (RH) falls below 40%.

2.4.3 Thermal Comfort

Thermal comfort is defined by the globally recognized standards for evaluating indoor environments, ASHRAE 55 and ISO 7730, as "that condition of mind that expresses satisfaction with the thermal environment". ASHRAE 55, developed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, establishes guidelines for thermal environmental conditions in occupied spaces to promote occupant comfort and well-being (Elder, 1979). It addresses factors such as temperature, humidity, air speed, and radiant heat, aiming to balance thermal comfort with energy efficiency.

The standard provides recommended ranges and metrics for indoor environmental conditions, enabling designers, engineers, and facility managers to optimize HVAC systems and create environments that support occupants' comfort, productivity, and overall satisfaction. ISO 7730, developed by the International Organization for Standardization, provides guidelines for evaluating and achieving thermal comfort in indoor environments. It defines parameters such as air temperature, humidity, air speed, and radiant heat, and establishes objective criteria for assessing thermal comfort based on human physiological responses and subjective feedback. The standard accounts for factors such as metabolic rates, clothing insulation, and outdoor climate conditions to provide a comprehensive framework for designing and maintaining comfortable indoor environments.

2.4.3.1 Predictive Mean Vote

Predictive Mean Vote is an index that aims to predict the mean value of votes of a group of occupants on a seven-point thermal sensation scale (Khan & Pao, 2015). As seen in the illustrations of Fanger's Theory in Figure 2, the PMV index has a +3 value for too hot and a -3 value for too cold.

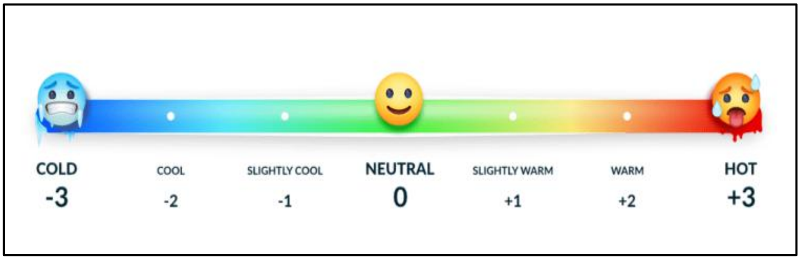


Figure 2. PMV index

2.4.3.2 Predicted Percentage of Dissatisfied

The PPD (Predicted Percentage of Dissatisfied) index estimates the percentage of occupants in a space who would be dissatisfied with the thermal conditions. Thermal comfort varies from 5% to 100%, depending on the occupant's location. To meet the standards set by ASHRAE 55 and ISO 7730, all occupied areas should maintain a PPD below 20%, and the recommended PMV range is between –0.5 and 0.5, according to ASHRAE 55. Fanger's Theory describes the relationship between PMV and PPD, as shown in Figure 3.

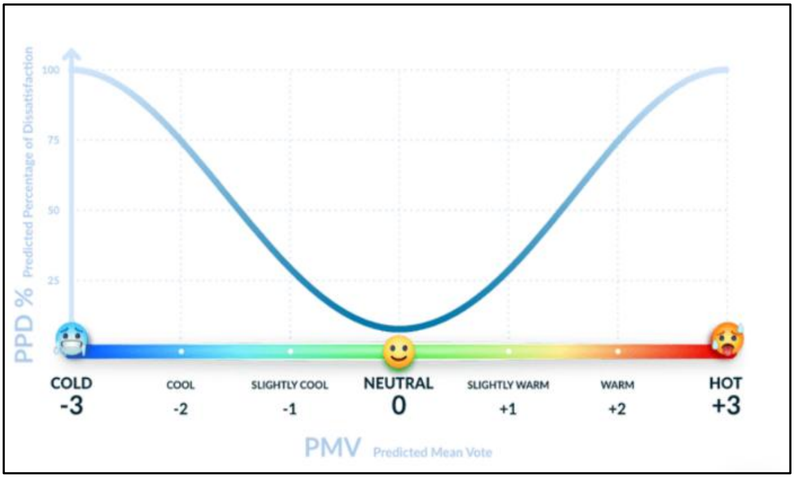


Figure 3. PPD index

2.4.3.3 Contaminant Removal Effectiveness (CRE)

The Contaminant Removal Effectiveness (CRE) is the ratio of the steady-state contaminant concentration in the exhaust duct to the steady-state mean concentration in the room. The effectiveness of contaminant removal in ventilation systems depends on factors such as the type and efficiency of the air filter, the airflow rate, the size and location of the contaminants, and the ventilation system's design and maintenance. One method for determining the CRE of a ventilation system is the Local Air Quality Index (LAQI). The LAQI measures pollutants in the air that can affect human health and the environment. It provides information on the effectiveness of a ventilation system in removing contaminated air. According to an article by Alkhalaf *et al*. (2023), an LAQI equal to one represents a perfectly mixed system. For LAQI greater than one, the ventilation system has a greater capability of removing contaminated air.

2.5 Validation and Statistical Treatment

Validation was conducted by comparing simulated air velocities and temperatures with design airflow specifications and ASHRAE 55 limits. Simulated velocity in occupied zones was verified to remain below 0.20 m/s. Mean, minimum, maximum, and standard deviation values were computed for each parameter across room sections and heights. Results were evaluated against standard threshold values for compliance assessment.

3. Results and Discussion

3.1 Flow Velocity

Determining the flow of air is crucial for evaluating thermal comfort and removing contaminants. It dictates where the air can reach in the room, based on its path from the inlet. Also, in terms of thermal comfort, the occupants of the room must not exceed 0.2 m/s, according to ASHRAE Standard 55.

Figure 4 illustrates the velocity contours of Rooms 1, 2, and 3. In Figure 4a, the velocity contour of the room in the front view is shown. The values and the swirling of air are concentrated near the inlet vent. Near the edge of the room, the results contrast with those near the inlet duct. The airflow is minimal in that area compared to other parts of the room. Figure 4b shows the contour in the top view, supporting the observations from the front view.

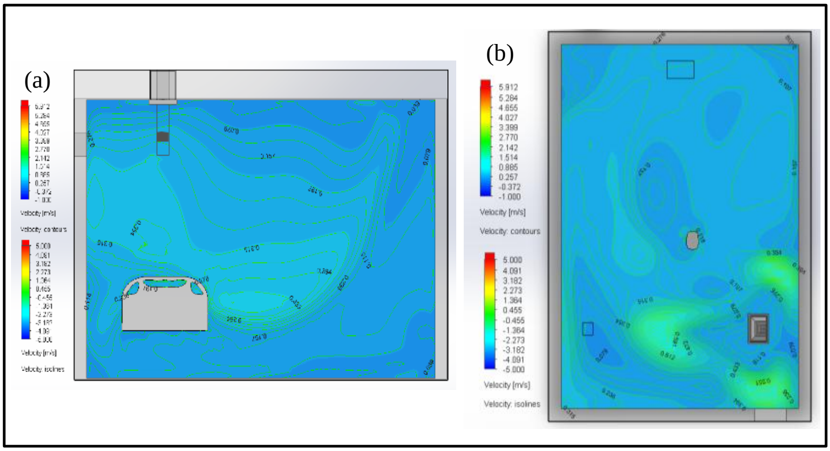


Figure 4. Velocity contour of rooms 1, 2, and 3 front view (a), top view (b)

Figure 5 shows the velocity contour for Room 4. Figure 5a is the front-view illustration of the velocity contour. There is good circulation in Room 4, as all corners of the room have adequate air circulation and air velocity. This claim is supported by the results in Figure 5b, where the velocity values on the contour can be observed. The highest velocity values are in the area near the inlet duct. While that may be the case, it is clearly shown in the figure that air is circulated well throughout the entire space.

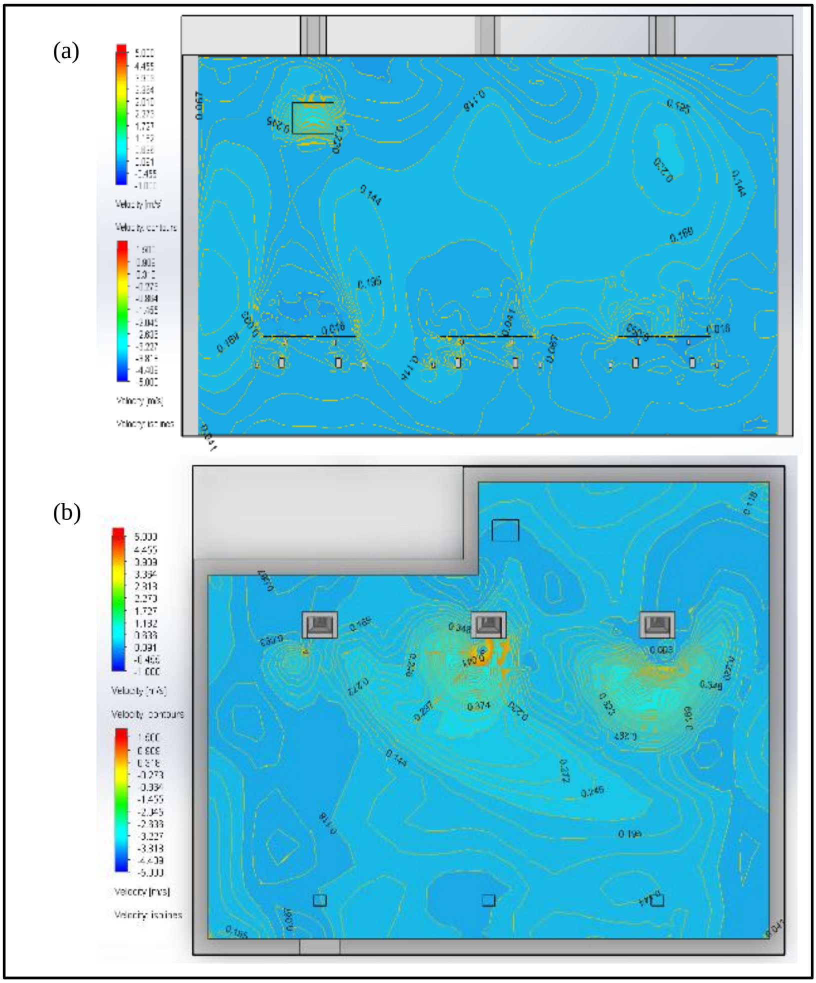


Figure 5. Velocity contour of room 4 front view (a), top view (b)

Figure 6 is the velocity contour of Rooms 5 and 11. As shown in Figure 6a, there is an aggressive contour of air located near the inlet duct. It can be observed that air is spread throughout the entire space of the room, which is a good indication of proper contamination removal and overall air comfort of the occupants. In Figure 6b, the top view of the space is observed. Near the inlet ducts is where the majority of the air velocity is located.

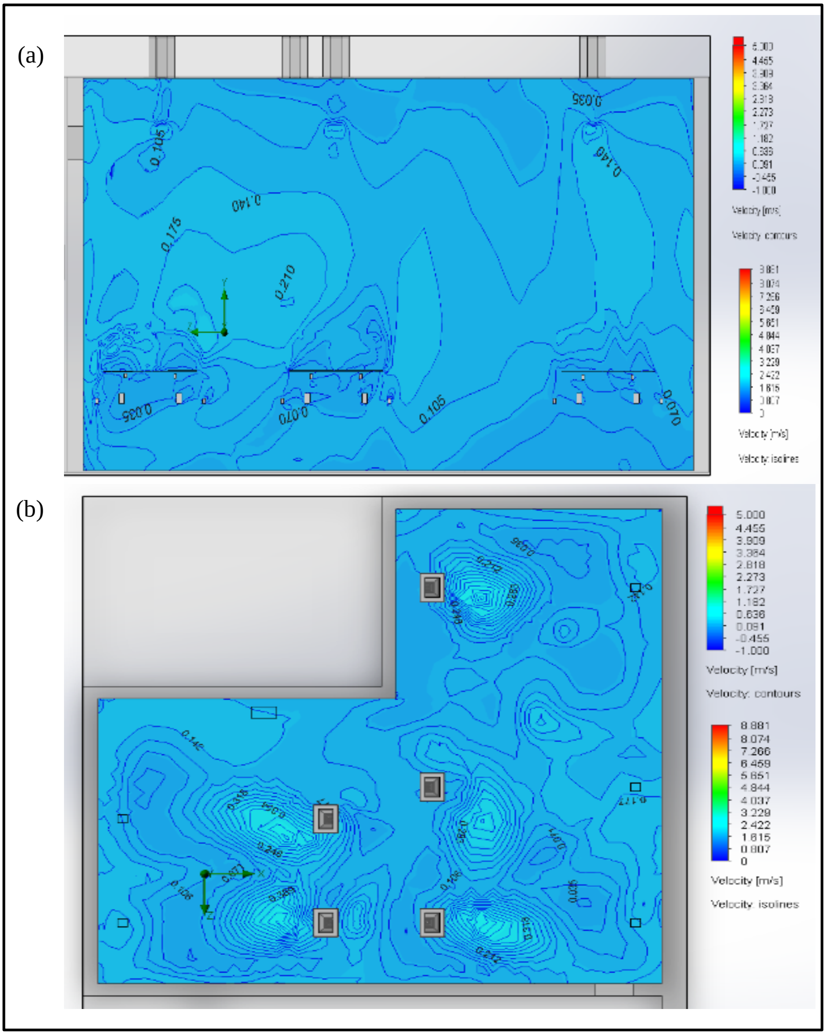


Figure 6. Velocity contour of rooms 5 and 11 front view (a), top view (b)

Figure 7 is the illustration of the velocity contour of rooms 6, 7, and 8. Figure 7a illustrates the front view of the space. It can be observed that the bed where the patient rests has its surrounding air circulated. The edges of the room are also reachable in the circulation of air. In Figure 7b, the top view of the space can be observed. The circulation of air from the inlet spreads throughout the entirety of the room, which is a good indication of the capability of the ventilation system to provide air circulation throughout the entire space.

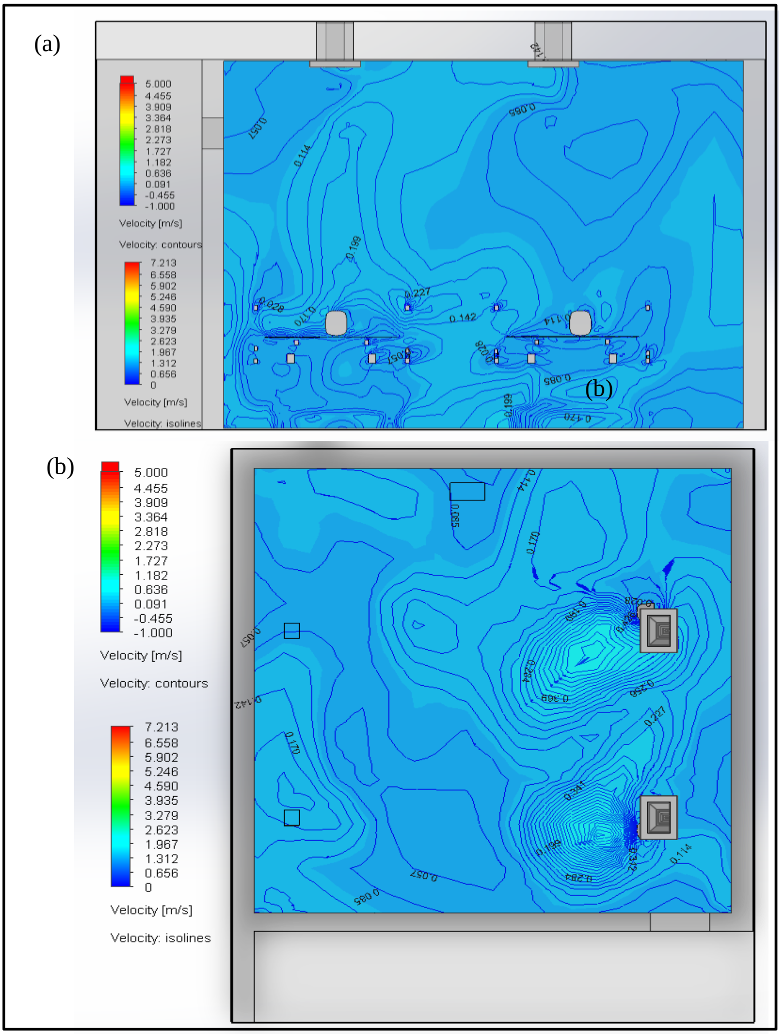


Figure 7. Velocity contour of rooms 6, 7, and 8 front view (a), top view (b)

Figure 8 is the illustration of the velocity contour of rooms 9 and 10. In Figure 8a, the air is circulated all over the room. The corners of the room are well circulated, except for the upper left portion of the room, where there is less air being circulated. The area in Figure 8b where there is less air circulation can be seen on the lower left.

Illustrated in Figure 9 is the velocity contour of rooms 12 and 13. In Figure 9a, a consistent circulation of air in the entirety of the room. Unlike the other rooms, Rooms 12 and 13 have a consistent flow of air that spreads throughout the entire room. In Figure 9b, the opposite can be seen in the lower part of the illustration, where there is less circulation in that area.

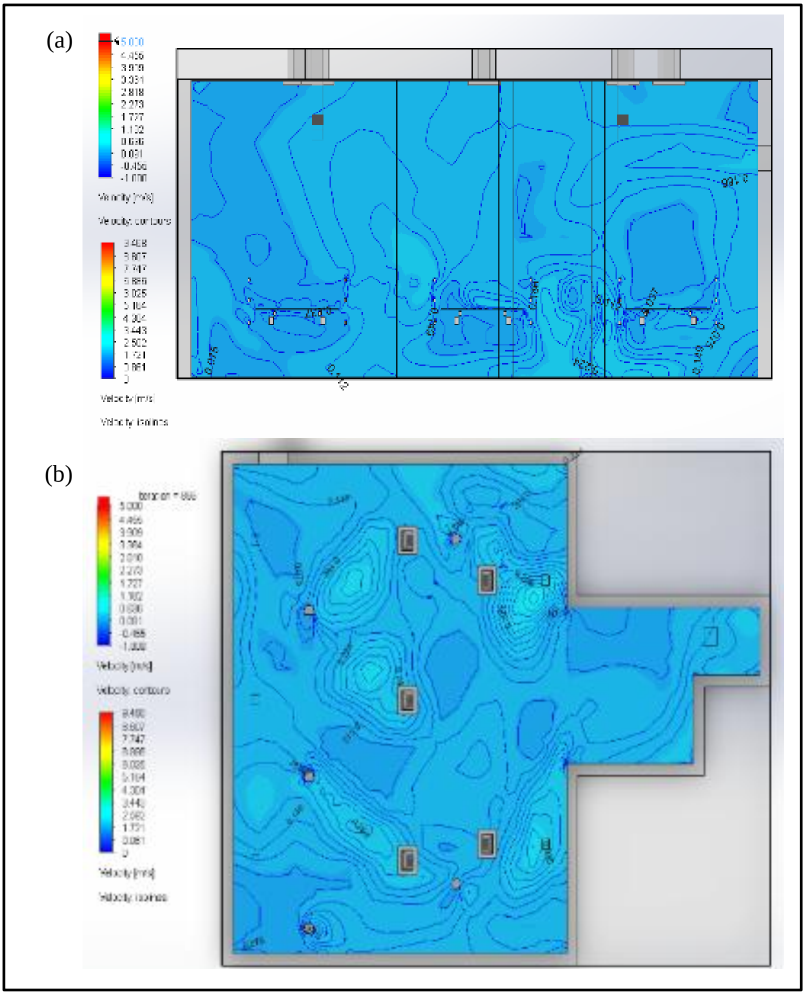


Figure 8. Velocity contour of rooms 9 and 10 front view (a), top view (b)

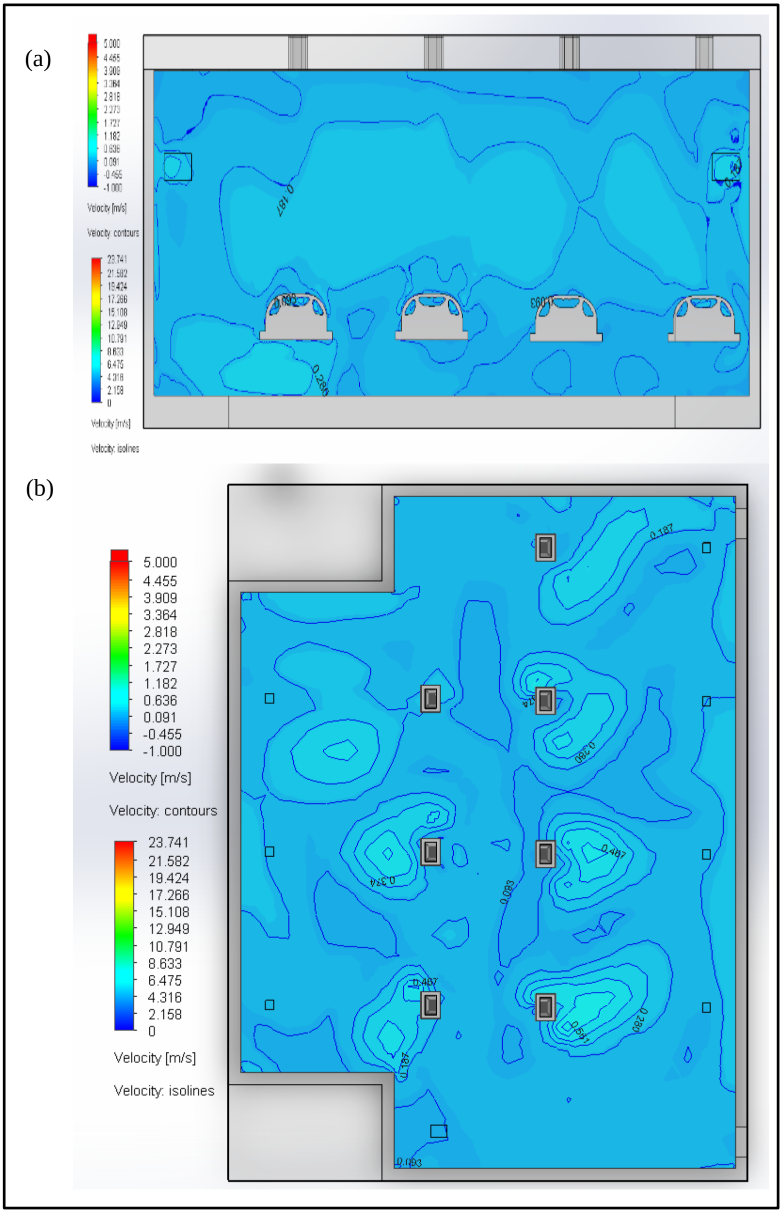


Figure 9. Velocity contour of rooms 12 and 13 front view (a), top view (b)

The CFD simulations revealed that airflow velocities in the hospital wards and COVID-19 enclosures were consistently maintained within the recommended range of 0.15–0.25 m/s. This velocity band is critical for balancing thermal comfort and draft sensation. At velocities below 0.15 m/s, stagnant air can lead to uneven temperature distribution and localized discomfort, while velocities above 0.25 m/s may cause drafts that patients perceive as chilling, particularly in recovery wards. By achieving stable velocities within this optimal range, the AHU design ensures that patients and healthcare staff experience a neutral thermal environment, reducing the risk of discomfort and enhancing overall satisfaction. This finding directly supports compliance with ASHRAE 55 standards, which emphasize maintaining air movement at levels that avoid both stagnation and excessive draft.

Beyond comfort, airflow velocity plays a decisive role in infection control within hospital environments. The simulations demonstrated that maintaining velocities between 0.15–0.25 m/s facilitated effective air mixing and minimized zones of stagnant air where contaminants could accumulate. This controlled velocity ensured that airborne pathogens were continuously diluted and directed toward exhaust outlets, thereby improving contaminant removal effectiveness (CRE > 1.0). In COVID-19 enclosures, where infection risk is heightened, the stable velocity distribution contributed to maintaining positive pressure gradients and preventing cross-contamination between zones. Thus, the velocity results not only validate the AHU's ability to meet comfort standards but also highlight its contribution to patient safety by supporting infection control protocols.

3.2 Temperature and Humidity

The findings highlight a crucial aspect of the behavior of air temperature, namely that air close to the ground tends to be colder than air at higher altitudes (Figure 10). This is explained by the fact that the ground loses heat more rapidly than the air does because of radiation and convection, among other causes. The air in touch with the ground, therefore, typically has a lower temperature than the air at higher altitudes.

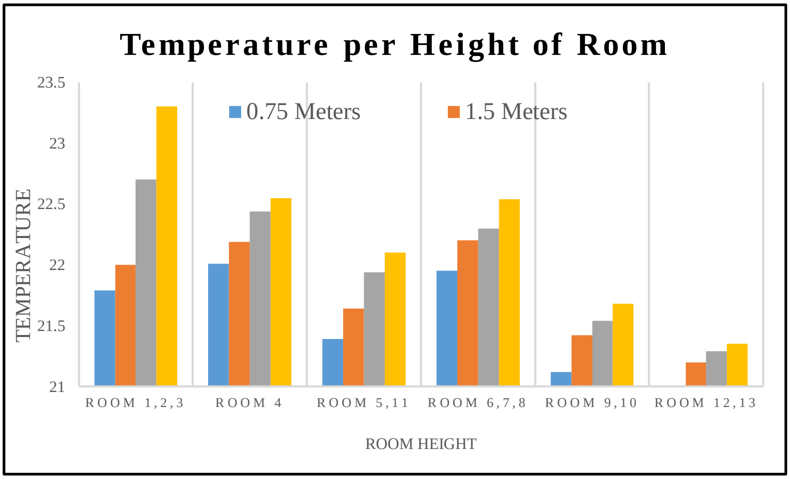
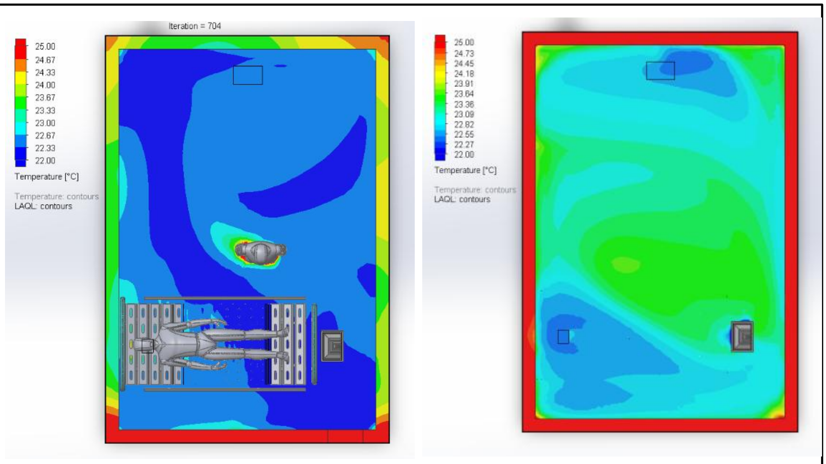


Figure 10. Temperature readings from every room for varying heights

Ignoring the amount of heat generated from the walls and around the patient and watcher, there are spots near the air-conditioner that are marked dark blue, while others section of the room is marked light blue. Comparing the results of the colored contour in the color chart of Figure 11, both figures have a clear temperature difference. In contrast, Figure 11a tends to have a lower temperature than Figure 11b.



(a) (b)

Figure 11. Room 1, 2, 3 temperature cut plot 0.75 meters (a), 3 meters (b)

This phenomenon can be compared to the study of Gamberini *et al.* (2020), where they observed how the air temperature reduced as it traveled closer to the ground using computational fluid dynamics simulations.

As illustrated in Figure 12, the relative humidity of all rooms falls within the range of 40% - 50%. Relative humidity is an important parameter in terms of comfort and safety. According to an overview by Fumo (2025), too little or too much humidity might harm people. Common viruses tend to thrive in environments where there is less or too much humidity. The optimal amount of relative humidity according to the study is between 40% and 60%.

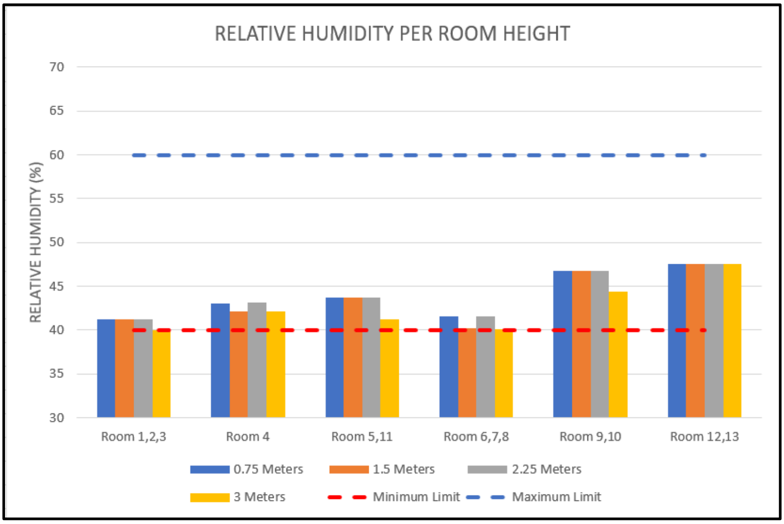


Figure 12. Relative humidity per room

The CFD simulations showed that indoor temperatures were consistently maintained between 21–23.5 °C, which falls within the recommended range for hospital environments. This stability is crucial for patient comfort, particularly for those in recovery wards where thermal neutrality supports healing and reduces stress. Maintaining temperatures within this band also ensures compliance with ASHRAE 55 and ISO 7730 standards, which emphasize thermal comfort as a determinant of patient satisfaction. Deviations outside this range could lead to discomfort, reduced staff productivity, and potential complications for patients with compromised thermoregulation. Thus, the AHU's ability to sustain optimal temperatures directly contributes to both patient well-being and operational efficiency.

Relative humidity was controlled within 40–50%, aligning with international guidelines for healthcare facilities. This range is critical because humidity levels below 40% can dry mucous membranes, increasing susceptibility to respiratory infections, while levels above 60% may promote microbial growth and mold formation. By maintaining humidity within the optimal band, the AHU design reduces the risk of airborne pathogen survival and transmission, thereby enhancing infection control. In COVID-19 enclosures, stable humidity levels also support the effectiveness of air filtration and contaminant removal, complementing airflow velocity in minimizing cross-contamination. The results highlight that humidity regulation is not only a comfort parameter but also a vital infection-prevention strategy in hospital ventilation systems.

3.3 Thermal Comfort

The well-being of the patients, watchers, and staff is vital, as it demonstrates the comfort of the patients while they are recuperating. The performance of the ventilation system lies in how effectively it brings comfort to the people present. An article by Wolkoff (2024) explained that there must be a thermal equilibrium inside the room to prevent sweating from high temperatures or shivering in cold temperatures. These phenomena can cause local discomfort for the residents of the room.

The PMV values translate to the thermal comfort that patients and the watchers felt during their stay in the room. As illustrated in Figure 13, only rooms 6, 7, and 8 have a slightly warm result, while the rest are within the neutral to slightly cold range. The only explanation is that rooms 6, 7, 8 are designed for 2 patients and 2 watchers. This means that the amount of body heat exerted by the four people in the room contributes to the heat that is dispersed through the environment (Su *et al.*, 2024).

Figure 14 illustrates the PPD % of every room. The simulated data has found that the percentage of PPD in every room is below 20%. This means that it falls within the standard given by ASHRAE 55, where for a particular environment to be comfortable, its PPD percentage should not exceed 20%.

According to the ASHRAE Standard 55, the preferred graph of the PMV vs PPD% rating must be between -1 and 1 on the PMV scale and under 20% in the PPD% ratings (Gorman *et al.*, 2020). Figure 15 illustrates the simulated data of the rooms arranged in order of decreasing to increasing value. The thermal comfort parameters of the rooms of the hospital are within the preferred values under the ASHRAE 55 standard.

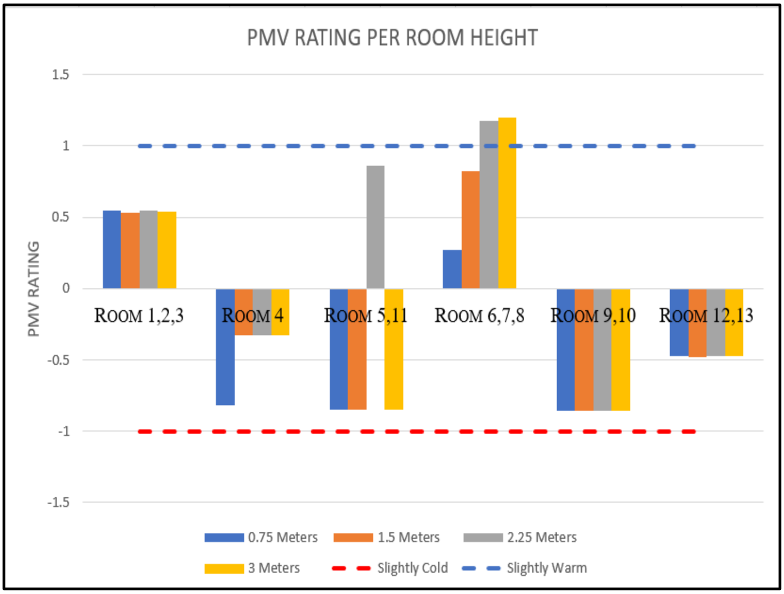


Figure 13. PMV ratings vs Room height

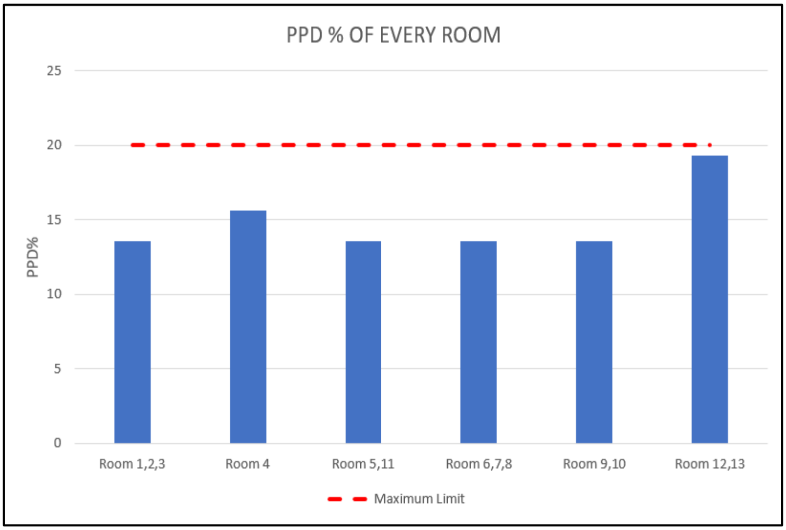


Figure 14. PPD% of every room

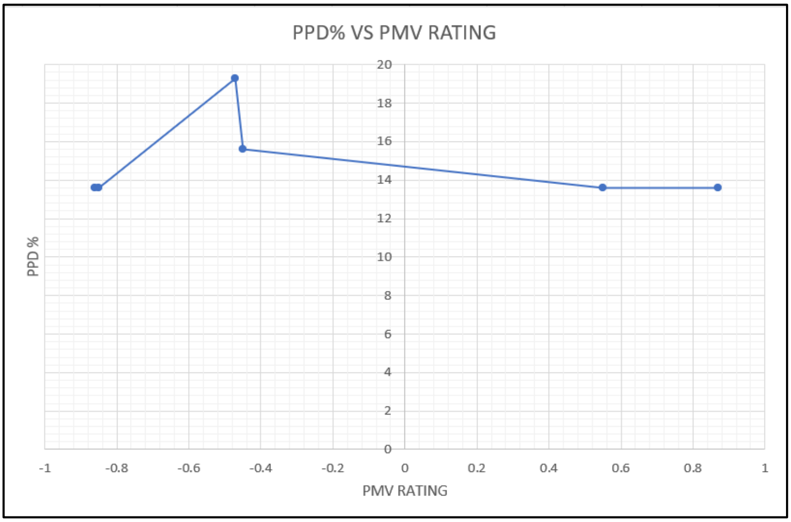


Figure 15. PMV vs PPD% rating

The CFD results indicated that thermal comfort indices, specifically Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), were consistently within acceptable ranges. PMV values between –0.5 and +0.5 correspond to a neutral thermal sensation, while PPD values below 20% indicate that the majority of occupants are satisfied with the indoor environment. For hospital wards, this is particularly important because patients often have reduced tolerance to thermal discomfort due to illness or recovery conditions. Staff productivity and alertness are also enhanced when thermal conditions are stable and comfortable. By achieving compliance with ASHRAE 55 and ISO 7730 standards, the AHU design ensures that both patients and staff experience an environment conducive to healing and effective healthcare delivery.

Thermal comfort is not only a matter of perception but also a determinant of operational efficiency and safety in hospitals. Maintaining PMV and PPD within recommended thresholds reduces the need for frequent manual adjustments to HVAC systems, thereby lowering energy consumption and operational costs. Furthermore, stable thermal conditions minimize the risk of condensation and microbial growth, which can compromise IAQ and patient safety. In COVID-19 enclosures, achieving thermal neutrality supports infection control by ensuring that airflow patterns remain consistent and do not create localized hot or cold spots where contaminants could accumulate.

Thus, the thermal comfort results highlight the dual benefit of enhancing occupant well-being while supporting efficient and safe hospital operations.

3.4 Contaminant Removal Effectiveness

The CRE ratings of every room are shown in Figure 16. As a result, every room has good contaminant removal capabilities. Rooms 12 and 13 bear the highest contaminant removal rating, while Rooms 1, 2, and 3 bear the lowest. An article by Mustafa *et al*. (2025) explained that when the CRE rating is greater than 1, then the ventilation system has a good tendency to remove contaminants in the room. Furthermore, in the studies of Lv *et al*. (2021) and Aflaki *et al*. (2019), the CRE rating of a ventilation system can be improved by increasing the ACH of the system.

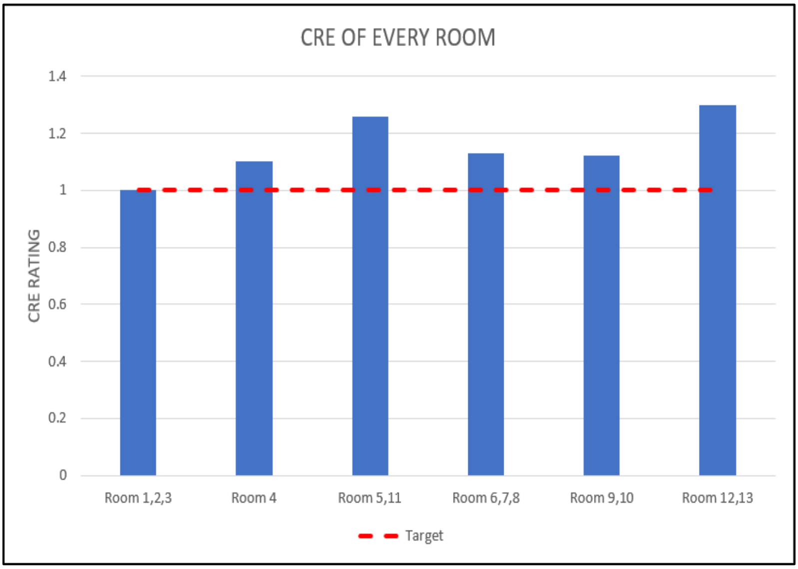


Figure 16. CRE rating of every room

3.4.1 Local Air Quality Index (LAQI)

Figure 17 illustrates the LAQI of the rooms, rooms 12 and 13 have the highest rating. This means that every measurement point in Rooms 12 and 13 shows good contaminant removal, while rooms 1, 2, 3 bear the lowest results. The increase in the ACH has a positive effect on the local air quality index of the rooms (Sarmadi *et al*., 2021).

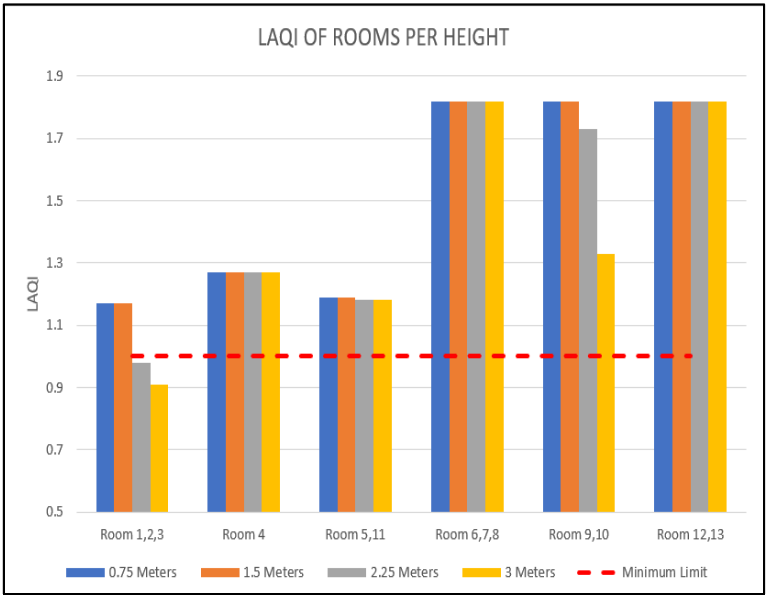


Figure 17. LAQI of rooms per height

The CFD simulations demonstrated that CRE values across all hospital wards and COVID-19 enclosures exceeded 1.0, indicating that the ventilation system was more effective at removing contaminants than a perfectly mixed system. This result validates the AHU design, showing that airflow distribution successfully directed pollutants toward exhaust outlets while minimizing recirculation. In practical terms, a CRE > 1.0 means that patients and staff are exposed to lower concentrations of airborne contaminants, thereby reducing the risk of infection transmission. This finding confirms that the AHU system not only meets but surpasses baseline ventilation requirements, ensuring a safer hospital environment.

High CRE values highlight the system's ability to maintain clean air zones, which is critical in sensitive hospital areas such as operating rooms and COVID-19 isolation wards. By achieving CRE > 1.0, the AHU design supports compliance with ASHRAE 170 guidelines for healthcare ventilation, which emphasize contaminant dilution and removal. In COVID-19 enclosures, elevated CRE values are particularly significant because they demonstrate that the system can effectively reduce viral particle concentration, complementing other infection control measures such as filtration and pressure differentials. This reinforces the importance of incorporating CRE analysis into hospital ventilation design, as it provides quantifiable evidence of system performance in safeguarding patient health.

The results of this study demonstrated that airflow velocity (0.15–0.25 m/s), temperature (21–23.5 °C), and relative humidity (40–50%) were consistently maintained within recommended ranges, ensuring both patient comfort and infection control. Thermal comfort indices further validated system performance, with PMV values between –0.5 and +0.5 and PPD below 20%, indicating compliance with ASHRAE 55 and ISO 7730 standards. Contaminant Removal Effectiveness (CRE) values exceeding 1.0 confirmed that the AHU design achieved superior pollutant dilution compared to a perfectly mixed system.

These findings align with the work of Le *et al*. (2022), who emphasized the role of CFD in optimizing airborne infection isolation rooms, but extend prior research by integrating multiple IAQ indices—PMV, PPD, LAQI, and CRE—into a single framework. Compared with Berlanga *et al*. (2018) and Alkhalaf *et al*. (2023), which focused primarily on airflow and contaminant transport, this study provides a more holistic evaluation of hospital ventilation performance. Collectively, the comparative analysis underscores that CFD-based validation of AHU systems not only ensures compliance with international standards but also enhances patient safety and operational efficiency in healthcare environments.

While the CFD simulations provide valuable insights into airflow distribution, thermal comfort, and contaminant removal, it is important to acknowledge that hospital environments are inherently dynamic. In practice, factors such as varying patient occupancy, frequent door openings, staff movement, and equipment heat loads introduce fluctuations that cannot be fully captured in steady-state simulations. Emergency scenarios, such as sudden increases in patient numbers or the use of portable medical devices, may also alter airflow patterns and contaminant dispersion. These operational complexities highlight the need for ongoing monitoring and adaptive ventilation strategies to complement the baseline performance demonstrated in the simulations.

Future work should incorporate transient CFD analyses to evaluate how the system responds to short-term disturbances, such as door swings or changes in occupancy density. Integrating real-time sensor data with simulation models could further enhance predictive accuracy, allowing facility managers to adjust ventilation rates dynamically. By acknowledging these complexities, the study emphasizes that while the designed AHU system meets international standards under controlled conditions, continuous validation and adaptive operation are essential to ensure consistent infection-control performance and patient comfort in real-world hospital settings.

4. Conclusion and Recommendation

The simulated design showed results for the flow of air and thermal comfort parameters. The air was circulated in all corners of the room except for Rooms 1, 2, and 3, where there is a minimal amount of air that flows in the right corner of the room. The thermal parameters of every room fall under safe and comfortable margins according to ASHRAE 55 standards. The temperature of the room from 0.75 meters to 1.5 meters is considerably colder compared to the temperature of 2.25 meters above. This means that the occupants of the room will be thermally comfortable throughout their stay.

The Relative Humidity of each room falls between the safety margin, PMV, and PPD values, which are within the comfortable levels. It is within the optimal values of ASHRAE standard 55. The calculated CRE values of every room are all greater than one. This means that each room has a good chance of removing contaminants in the air via the ventilation system. Every LAQI of the results of the rooms except rooms 1, 2, and 3 has a good overall LAQI, which correlates to the values of the calculated CRE.

The CFD evaluation of the Air Handling Unit (AHU) system in the hospital wards and COVID-19 enclosure demonstrates that airflow velocity, temperature, relative humidity, and thermal comfort indices (PMV and PPD) generally comply with ASHRAE 55 and ISO 7730 standards. Contaminant Removal Effectiveness (CRE) values greater than 1.0 indicate adequate ventilation performance, while acceptable LAQI values confirm efficient contaminant dilution in most areas. However, localized low-velocity regions and minor airflow recirculation observed in selected rooms suggest opportunities for optimization.

To reinforce the practical impact of this study, the following recommendations are proposed: reposition or redesign supply diffusers in rooms exhibiting recirculation to improve airflow uniformity (1); conduct airflow balancing and periodic commissioning to ensure consistent Air Changes per Hour (ACH)

(2); integrate real-time monitoring sensors for temperature, humidity, and CO_2 to validate CFD predictions during actual operation (3); consider slight increases in supply airflow in low-performing zones while maintaining thermal comfort thresholds (4); and incorporate CFD-based evaluation as a standard design verification tool for future hospital expansions or retrofits (5). Implementing these measures will enhance ventilation efficiency, infection control, and patient comfort while ensuring long-term HVAC system reliability.

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