Enhancing Indoor Air Quality and Minimizing Airborne Virus Dispersion Under Various Ventilation Strategies While Maintaining Thermal Comfort

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Abstract

Indoor air quality (IAQ) and thermal comfort are critical factors that influence occupant health, productivity, and general well-being in office environments. The COVID-19 pandemic has further highlighted the importance of effective ventilation strategies in mitigating the transmission of airborne viruses. This research investigates the performance of three ventilation strategies: indoor recirculation systems (4-way ceiling cassette air conditioners), natural ventilation, and mixed mode ventilation (AC + natural ventilation) in maintaining optimal IAQ, thermal comfort, and infection control in an open-plan office setting. Using a combination of computational fluid dynamics (CFD) simulations and real-world environmental monitoring, this study evaluates airflow patterns, pollutant dispersion, and thermal regulation under different ventilation conditions.

This thesis explicitly demonstrates that IAQ, thermal comfort, and airborne virus transmission are deeply interconnected. Poor air quality not only impairs comfort and productivity but also prolongs aerosol suspension time, elevating infection risk. As such, ventilation strategies must be designed to address these three aspects holistically.

The findings reveal that the air conditioning (AC) system, while providing controlled air distribution, often leads to stagnation zones that reduce air mixing efficiency and increase pollutant accumulation. Natural ventilation, though beneficial under favourable conditions, exhibits inconsistent performance due to external weather variations, leading to excessive humidity fluctuations and temperature instability. In contrast, mixed mode ventilation emerges as the most effective strategy, offering improved airflow uniformity, improved pollutant dilution, and greater adaptability to seasonal changes. The results demonstrate that a well-optimised hybrid system, which strategically combines an AC system and natural ventilation, can mitigate the limitations of standalone approaches by balancing fresh air intake, controlled temperature regulation, and efficient humidity management.

This research contributes to a novel integrated methodological framework that bridges CFD simulations with IoT-based environmental monitoring, ensuring robust validation of ventilation performance under real-world conditions.

The findings have significant implications for the optimisation of heating, ventilation and air conditioning (HVAC) and public health policies, particularly in the post-pandemic era, where IAQ is a major concern. By addressing critical knowledge gaps in ventilation performance, this thesis provides practical recommendations for facility managers, architects, and policy makers to develop more resilient and health-conscious indoor environments.

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List of Publications

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- CO2 Monitoring as an Indicator of Ventilation Performance in a Teaching Office (Under review)

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Chapter 1

Introduction

In recent years, the quality of indoor environments has gained increasing attention due to its direct impact on public health, energy use, and building sustainability. The COVID-19 pandemic has further underscored the importance of managing indoor air quality (IAQ), thermal comfort (TC), and ventilation to minimise airborne virus transmission risks [1]. This research sits at the intersection of environmental engineering, building design, and public health, aiming to optimise indoor conditions in office environments through a robust, simulation-backed evaluation of ventilation strategies. By addressing the dynamic relationships between IAQ, TC, and airborne pathogen dispersion, the study provides timely insights that are vital to both the architecture-engineering-construction (AEC) sector and health-focused policy development.

1.1 Indoor Air Quality

To define air quality, it is crucial to establish a baseline for what constitutes "clean" or "standard" air. Clean air typically refers to dry atmospheric air found in remote and unpolluted areas, such as rural locations or over the ocean, where anthropogenic and natural pollutants are minimal [2]. These areas are considered ideal baselines because they provide a reference point that closely approximates the natural state of the atmosphere before significant human intervention. Table 1.1 provides an overview of the chemical composition of clean and dry atmospheric air, serving as a reference for air quality assessments. In particular, atmospheric air also contains varying amounts of water vapour (0.1% to 3%), influenced by temperature and environmental conditions [2]. Although Table 1.1 outlines the standard composition of clean air, trace amounts of other components, including ammonia, sulphur dioxide, formaldehyde, carbon monoxide, iodine, sodium chloride, and particulate matter (PM; e.g., dust and pollen), may still be present within acceptable limits of 'clean' air [2].

Based on this standard, air quality is defined by the degree to which it deviates from clean air due to the presence of pollutants. Air quality improves as pollutant concentrations decrease. Any substance in the air that adversely affects the health, comfort, or productivity of humans and animals, hinders plant growth, or accelerates equipment degradation is classified as an airborne pollutant. Airborne pollutants may exist as solid particles (e.g., PM, dust, and pollen), liquid droplets (e.g., aerosols and vapours), or gases (e.g., carbon monoxide, nitrogen oxides, and volatile organic compounds; VOCs) [2].

Substance	Content (% a In volume)	Concentration (ppm a In volume)
Nitrogen	78.084 ± 0.004	780,840
Oxygen	20.946 ± 0.002	209,460
Argon	0.934 ± 0.001	9,340
CO2	0.033 ± 0.001	330
Neon		18
Helium		5.2
Methane		1.2
Krypton		0.5
Hydrogen		0.5
Xenon		0.08
Nitrogen dioxide		0.02
O3		0.01-0.04

Table 1.1: Chemical Composition and Volumetric Content of Typical Dry Atmospheric Air [2]

Note: Percentage values for some trace gases are not reported in the original source and are thus omitted.

1.1.1 Importance of Indoor Air Quality

With individuals spending more than 90% of their time indoors in many regions, indoor air quality (IAQ) has become a critical determinant of health and well-being [3]. Air quality in homes, offices, and other enclosed spaces significantly affects occupant comfort, productivity, and cognitive performance [4]. IAQ can be improved through various approaches, including fostering green environments through plant-based solutions, adopting nonpharmaceutical interventions, and employing engineering controls. Engineering strategies, such as adequate ventilation, air filtration systems, and pollutant control mechanisms, have been shown to be effective in improving IAQ [5].

IAQ in office environments directly impacts employee health and productivity. Research has consistently shown that pollutants such as PM, VOCs, formaldehyde, and carbon dioxide (CO2) frequently exceed recommended levels [6, 7]. Pollutant levels often peak during working hours and colder months [7], correlating with increased reports of symptoms such as fatigue, headaches, and dryness of the air, which are commonly associated with sick building syndrome [8]. Poor IAQ has been associated with higher health complaints, increased absenteeism, and reduced workplace productivity [9].

1.1.2 Strategies to Improve Indoor Air Quality

To address the challenges in the previous section, building managers and facility operators should monitor key IAQ parameters, manage pollution sources, and adopt appropriate ventilation strategies. Providing personalised controls, such as adjustable temperature and ventilation settings, further enhances occupant satisfaction and workplace productivity [9]. These measures enable organisations to mitigate the adverse effects of poor IAQ, fostering a healthier and more conducive work environment. In addition, integration of air-cleaning technologies, such as HEPA filters, activated carbon filters, and ultraviolet germicidal irradiation (UVGI), can help remove pollutants and pathogens effectively.

1.1.3 Indoor Environmental Quality

Indoor environmental quality (IEQ) encompasses several factors, including IAQ, pollution levels, ventilation, thermal comfort (TC), lighting, and acoustics. IAQ is considered satisfactory when harmful levels of chemical and biological pollutants are absent and most of the inhabitants do not express dissatisfaction. However, indoor environments are often characterised by elevated concentrations of various pollutants from both internal and external sources. Key pollutants in office environments include ozone (O3), VOCs, aldehydes, PM (PM2.5 and PM10), and ultrafine particles (UFPs). These pollutants originate from sources such as electronic devices, building materials, furniture, occupant activities, and cleaning products. Poor IAQ not only poses health risks but also negatively impacts TC, which is a critical factor in overall satisfaction with IEQ. TC refers to the "condition of mind that expresses satisfaction with the thermal environment." It is commonly assessed using metrics such as air temperature, mean radiant temperature, air velocity, intensity of turbulence, and relative humidity [9]. Maintaining both IAQ and TC is essential for creating safe, healthy, and productive indoor spaces.

Indoor Environmental Quality particularly thermal comfort and Indoor Air Quality significantly influences occupants' health and well-being [10]. Furthermore, studies have shown that inadequate IAQ contributes to airborne virus transmission, making it essential to consider IAQ and thermal factors together when designing infection control strategies [11].

1.2 Respiratory Viruses

Respiratory viruses, such as influenza, respiratory syncytial virus (RSV), parainfluenza, adenovirus, rhinovirus, and coronaviruses, have a significant global health impact, particularly among vulnerable populations such as children, the elderly, and immunosuppressed individuals [12]. These viruses primarily cause upper respiratory tract infections, which can progress to severe lower respiratory tract complications, leading to high healthcare costs and higher mortality rates [13].

The COVID-19 pandemic caused by SARS-CoV-2 underscored the widespread threat of respiratory viruses. Public health and social measures (PHSMs) implemented during the pandemic, such as physical separation, mask use, and improved ventilation, were effective in reducing the incidence and transmission of several respiratory viruses from 23% to 98% [14]. However, as restrictions eased, non-COVID respiratory viruses re-emerged, often outside their usual seasons [15].

Office environments are particularly vulnerable to the transmission of SARS-CoV-2 due to close physical interactions, shared spaces, and inadequate ventilation [16]. Research confirms that respiratory viruses can remain viable in aerosols for hours and on surfaces for days, further highlighting the need for effective mitigation strategies in indoor environments [17].

1.2.1 Transmission Methods

Respiratory viruses, including influenza, RSV, rhinovirus, adenovirus, and coronaviruses such as SARS-CoV, predominantly target the upper respiratory tract and are recognised as significant human pathogens. Their potential to cause widespread outbreaks and pandemics, combined with their socio-economic implications, underscores their importance to public health [12].

Transmission occurs through four primary mechanisms [18–20]:

- Direct contact: Physical interactions, such as handshakes or touching infected individuals, facilitate the direct transfer of pathogens.
- Indirect contact via foams: Contaminated surfaces act as intermediaries, allowing the transfer of viruses when touched by susceptible individuals.
- Respiratory droplets: Larger particles (>5 µm) expelled during coughing, sneezing, or talking usually settle quickly on surfaces or within short distances.
- Aerosols: Smaller particles (< 5 µm) remain suspended in the air for extended periods, increasing the potential for airborne virus transmission, particularly in poorly ventilated spaces.

Understanding these transmission pathways is crucial for developing targeted and effective mitigation strategies. In office settings, such strategies include optimising ventilation, implementing physical distancing protocols, and maintaining regular cleaning and disinfection routines to minimise viral spread.

1.3 Modelling

Computational Fluid Dynamics (CFD) is a powerful tool to simulate airflow, temperature distribution, and dispersion of airborne contaminant in indoor environments. The importance of CFD in the evaluation of ventilation strategies has increased significantly, particularly in the wake of the COVID-19 pandemic, where optimising air circulation has become crucial for infection control.

In this research, CFD simulations were used to compare the effectiveness of air conditioning (AC), natural, and mixed mode ventilation strategies to mitigate the transmission of airborne viruses and maintain TC. By integrating real-world sensor data (including concentrations of CO2, humidity, and PM), the precision of CFD predictions was validated, ensuring robust and reliable results. This approach allows for a detailed analysis of airflow stagnation (dead zones), viral particle dispersion, and the ability of different ventilation methods to regulate IAQ and TC.

The findings of this CFD-based investigation not only contribute to a deeper understanding of IAQ dynamics but also offer practical insights into how ventilation systems should be designed and operated to improve occupant health and productivity.

1.4 Thermal Comfort

TC in indoor environments, particularly offices, is a multifaceted concept that is influenced by factors such as air temperature, humidity, air movement, and heat generated by occupants and electronic devices [21]. It is defined as the state in which individuals feel satisfied with the thermal environment, achieved when the heat produced by metabolism is balanced with the heat lost from the body. However, this perception is subjective because TC varies between individuals due to physiological factors and environmental conditions, including room temperature, air velocity, RH, and radiant temperature, as illustrated in Figure 3.1 [22].

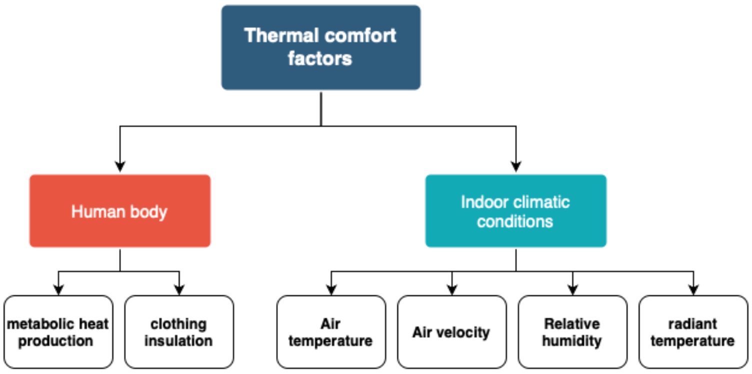


Figure 1.1: TC factors

1.4.1 Assessment of Thermal Comfort

Two widely used approaches to assess TC are the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD), developed by Fanger [23].

- PMV quantifies the thermal sensations of the residents on a scale ranging from -3 (cold) to +3 (hot), with 0 (neutral) representing thermal neutrality.
- PPD estimates the percentage of occupants likely to express dissatisfaction with the thermal environment. A PPD value of 10% or less is generally considered the threshold for acceptable levels of TC.

These indices provide a systematic framework for evaluating and optimising indoor thermal conditions.

1.4.2 Role of Computational Fluid Dynamics

TC assessments often use CFD as a cost-effective and efficient alternative to experimental methods, which can be both time-intensive and expensive [22]. CFD simulations allow for a detailed analysis of airflow patterns, temperature distributions, and humidity levels within indoor spaces. By modelling these parameters, researchers and engineers can optimise heating, ventilation and air conditioning (HVAC) systems and ventilation strategies to improve comfort and energy efficiency.

Recent studies have demonstrated the effectiveness of CFD in predicting TC in various indoor environments, including offices, classrooms, and theatres [24]. These simulations provide insights into the following.

- Airflow optimisation: Identify areas with stagnant air or uneven temperature distribution.

- System design improvements: Enhancing HVAC systems to achieve balanced thermal conditions.

1.5 Research Motivation

The motivation for this research comes from the increasing concern about IAQ and its critical role in the transmission of respiratory viruses, especially in office environments where occupants spend extended periods in enclosed spaces. The COVID-19 pandemic has highlighted the urgent need for effective strategies to mitigate the spread of indoor airborne infections. However, despite advances in IAQ management, several critical research gaps remain unaddressed, including:

- Integration of airborne virus transmission dynamics and TC: Although many studies focus on improving IAQ or optimising TC individually, there is a lack of comprehensive models that integrate airborne virus transmission dynamics with TC parameters. A holistic understanding of how ventilation strategies affect both infection risk reduction and occupant comfort is essential to designing healthier and more productive office environments.
- Comparison of ventilation strategies: Limited knowledge exists on how different ventilation strategies, such as AC, natural ventilation, and mixed-mode ventilation, perform to balance IAQ improvements with TC. Understanding the trade-offs between infection risk reduction and maintaining comfortable indoor conditions is critical for identifying optimal ventilation approaches.
- CO2 levels as indicators of airborne virus transmission risk: Although CO2 levels are widely used as a proxy for ventilation effectiveness, their reliability as direct indicators of airborne virus transmission risk is not fully

understood. More research is needed to evaluate whether CO2 concentrations can predict the likelihood of airborne virus transmission and guide real-time ventilation adjustments while maintaining TC.

By addressing these gaps, this research aims to provide practical insights that will contribute to the design of safer and healthier indoor environments without compromising occupant comfort. The findings will have significant implications for HVAC management and infection control strategies, offering actionable solutions to reduce health risks while ensuring a comfortable indoor climate in office settings.

1.6 Aim and Objectives

1.7 Aim and Objectives

Research Aim: This thesis aims to investigate how different ventilation strategies influence indoor air quality (IAQ), thermal comfort (TC), and the transmission of respiratory viruses by airborne viruses in office environments. By combining a detailed literature review, computational simulations, and experimental data, the study aims to identify optimal ventilation configurations that improve the health and comfort of the occupant while reducing the risk of infection.

Research Questions and Objectives: To achieve this aim, the following research questions and their corresponding objectives are addressed throughout the thesis:

- **Research Question 1:** How are viral particles transmitted within indoor environments, and what factors influence their transmission dynamics? **Objective 1:** To critically review and synthesise the existing literature on airborne virus transmission mechanisms in indoor environments, examine the key factors influencing transmission dynamics, and evaluate current strategies used to minimise virus spread.

- **Research Question 2:** Can CO2 levels serve as reliable indicators to assess IAQ and signal the potential risk of airborne infections in office environments? **Objective 2:** To evaluate CO2 concentration as a proxy of ventilation effectiveness and potential infection risk through real-world sensor data and CFD modelling.
- **Research Question 3:** What ventilation strategies can be implemented to minimise the risk of airborne infections in office environments? **Objective 3:** To investigate and compare the performance of AC, natural and mixed-mode ventilation systems to reduce the spread of airborne viruses.
- **Research Question 4:** How can ventilation systems be configured to maintain a good IAQ, ensure TC, and reduce virus dispersion in the office environment? **Objective 4:** To identify and propose optimal ventilation configurations that achieve a balance between infection control, improvement of IAQ, and thermal comfort based on seasonal and operational variations.

By addressing these research questions and objectives, this study provides an integrated assessment of airborne virus transmission control, IAQ optimisation, and occupant comfort in office settings. The insights gained are intended to guide practical ventilation strategies in the design and operation of post-pandemic buildings.

1.8 Research Contribution

This research makes a significant contribution to the fields of indoor air quality (IAQ), thermal comfort (TC) and airborne virus mitigation by providing a comprehensive analysis of ventilation strategies in office environments. Using Computational Fluid Dynamics (CFD) simulations supported by real-world IAQ sensor data, the study offers quantitative insights into how air conditioning (AC), natural and mixed-mode ventilation systems affect airflow distribution, pollutant removal, and TC.

The key contributions of this research are directly aligned with the formulated research questions:

- **(RQ1)** A comparative evaluation of ventilation strategies: This study systematically examines how AC, natural, and mixed-mode ventilation influence viral particle dispersion, air velocity patterns, and comfort metrics, providing insight into airborne virus transmission dynamics in indoor environments.
- **(RQ2)** Analysis of CO2 as an IAQ indicator: By incorporating sensor-based CO2 measurements, the study evaluates CO2's role as a proxy for ventilation effectiveness and its potential to signal elevated airborne infection risk.
- **(RQ3, RQ4)** Identification of airflow inefficiencies: The research reveals dead zones in both AC and natural ventilation scenarios—areas where pollutants and viruses may accumulate—informing better design of air distribution systems.
- **(RQ3, RQ4)** Practical recommendations for improving ventilation systems: Based on simulation and experimental results, the research proposes evidence-based configurations and strategies to optimise IAQ, minimise virus transmission, and maintain acceptable TC in office settings.

1.9 Thesis Overview

This thesis is structured to systematically explore the interactions between IAQ, ventilation strategies, and TC, with a particular focus on reducing airborne virus transmission in office environments.

Chapter 1: Introduction: This chapter establishes the importance of IAQ, thermal comfort, and airborne virus transmission in indoor environments. It outlines the research motivation, objectives, and contributions while identifying key research gaps. The research questions that guide the study are presented, forming the foundation for the subsequent analysis.

Chapter 2: Literature Review: This chapter addresses Research Question 1, providing a comprehensive review of airborne virus transmission in indoor environments. This chapter examines key factors that influence airborne virus transmission, including airflow dynamics, humidity, and temperature. It also reviews existing ventilation standards and mitigation strategies, highlighting current limitations and knowledge gaps in the field.

Chapter 3: Methodology: This chapter details the research design, including CFD simulations, sensor data integration, and experimental setups used to assess ventilation performance, TC, and virus dispersion.

Chapter 4: CO2 as an Indicator of IAQ and the Risk of Airborne Infections: This chapter addresses Research Question 2, evaluating whether CO2 concentration levels serve as a reliable proxy for IAQ and infection risk. This chapter presents experimental data to assess the correlation between CO2 levels, ventilation effectiveness, and airborne virus transmission.

Chapter 5: AC System Analysis: This chapter addresses Research Question 3, investigating how fully air-conditioned (AC) spaces manage airflow, pollutant dispersion, and thermal comfort. It examines whether AC alone is effective in mitigating airborne virus transmission and identifies potential limitations such as stagnant air zones.

Chapter 6: Natural Ventilation Analysis: This chapter addresses Research Question 3 and Research Question 4, assessing the effectiveness of natural ventilation configurations, particularly cross-ventilation, in maintaining IAQ and thermal comfort. Four NV scenarios are simulated under various environmental conditions, revealing the benefits and limitations of NV in different seasons. The chapter also evaluates virus dispersion, humidity control, and occupant comfort under varying window configurations and wind conditions.

Chapter 7: Mixed-Mode Ventilation Analysis : This chapter addresses Research Question 3 and Research Question 4, evaluating the effectiveness of combining AC and natural ventilation (mixed-mode ventilation) in improving IAQ and occupant comfort. Three Mixed-Mode scenarios are simulated under different environmental conditions, revealing the benefits and limitations of Mixed-Mode in different seasons. The chapter also evaluates virus dispersion, humidity control, and occupant comfort under varying Mixed-Mode configurations.

Chapter 8: Conclusion: This final chapter revisits the key findings in relation to each research question, summarising how the study contributes to the understanding of IAQ, ventilation strategies, and virus mitigation. This chapter provides recommendations for optimising ventilation in office environments and discusses potential avenues for future research.

1.10 Conclusion

This chapter has established the foundational context for this thesis, highlighting the critical importance of IAQ in office environments and its pivotal role in the airborne virus transmission. It has emphasised the growing challenges of balancing effective infection control with maintaining TC and optimising ventilation systems, particularly in light of recent global health crises, such as COVID-19.

This chapter has also identified significant research gaps to understand the complex interaction between airborne virus transmission dynamics, ventilation strategies, and the use of CO2 as a potential proxy of infection risk. Addressing these gaps requires a holistic approach that integrates advanced simulation tools, such as Ansys Fluent, and real-world environmental sensor data to investigate airflow patterns, TC, and viral dispersion under various ventilation scenarios.

To bridge these gaps, this thesis adopts a series of targeted research questions focused on airborne virus transmission, the reliability of CO2 as an IAQ indicator, and the development of engineering solutions to optimise ventilation. By systematically exploring these aspects, this research aims to deliver practical and innovative solutions to achieve healthier and more sustainable indoor environments.

Furthermore, the integration of IAQ improvements with occupant comfort and infection control highlights the multidisciplinary nature of this study, ensuring that its findings are not only theoretically robust but also applicable in real world settings. The contributions of this research are expected to inform the design of indoor spaces that prioritise occupant health, enhance TC, and minimise the risks associated with the transmission of airborne viruses.

This chapter sets the stage for the comprehensive exploration of the relevant literature, detailed methodologies, and critical findings in the following chapters. Through this structured approach, this thesis aims to provide actionable insights and engineering solutions that contribute to improved IAQ management and safer and more comfortable office environments.

Chapter 2

Literature Review

2.1 Introduction

This chapter addresses **Research Question 1 (RQ1)**: *How are viral particles transmitted within indoor environments, and what factors influence their transmission dynamics?* To explore this, the literature review examines transmission mechanisms of respiratory viruses, environmental and physical influences on dispersion, and strategies used to mitigate airborne transmission in indoor environments, especially offices. By synthesising current knowledge, this chapter lays the groundwork for identifying research gaps that motivate the computational and experimental investigations in later chapters.

Given that individuals spend approximately 90% of their time indoors, IAQ has emerged as a critical factor influencing not only health and comfort but also productivity within built environments[25]. This chapter addresses the multifaceted dimensions of IAQ, focusing on air pollutant concentrations and the increasing necessity for measures to prevent the spread of airborne viruses, such as SARS-CoV-2. Various precautions have been recommended, including reducing shared space capacities, increasing ventilation rates, employing natural ventilation, minimizing air recirculation, and avoiding direct exposure to airflow[26]. Furthermore, public health interventions such as lockdowns and the use of face masks have proven effective in curbing infection rates[27].

While these measures effectively control the spread of respiratory infections, additional environmental parameters such as temperature, relative humidity (RH), and evaporation—also play an important role in influencing virus transmission [28]. Experts recommend fundamental strategies to enhance IAQ and mitigate the risk of airborne infections, including adequate ventilation, air filtration, humidity regulation, and temperature control [29].

The role of ventilation in controlling airborne transmission has been consistently highlighted in the literature [30, 31]. Properly managing room air distribution patterns and airflow rates is essential to optimize indoor air circulation [32, 33]. During pandemics, international organizations such as American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and Federation of European Heating, Ventilation and. Air Conditioning Associations (REHVA) have emphasized the importance of increasing outdoor air ventilation [34]. However, careful consideration must be given to prevent contamination risks and potential recirculation of infected air [35].

Effective IAQ management also involves filtering outdoor air using appropriately sized high-efficiency particulate air (HEPA) filters, which have proven effective in removing viral particles and pollutants that exacerbate COVID-19 transmission risks [36]. Additionally, monitoring CO2 levels in indoor environments as an indirect method to assess infection risk is essential because CO2 concentration can be a key indicator of ventilation adequacy in relation to human respiratory activityPang et al. [34].

Research on how SARS-CoV-2 spreads within indoor environments has become a focal point of IAQ studies, particularly in terms of airborne transmission pathways [37]. The virus can remain viable on surfaces for days and in aerosols for hours, necessitating a thorough understanding of transmission routes to implement effective prevention strategies [17].

The integration of digitalization technologies, such as Digital Twins and Internet of Things (IoT) devices, offers new possibilities for managing IAQ. These technologies enable virtual planning, real-time monitoring, and predictive maintenance, contributing to improved IEQ management [38–41]. Moreover, the analysis of unstructured Big Data generated by IoT devices, when combined with artificial intelligence (AI) techniques such as machine learning (ML) algorithms, can provide valuable insights for optimizing IAQ [40, 41]

In addition to technological advancements, both experimental and CFD analyses have been employed to study aerosol behaviour and airborne transmission in indoor spaces[42, 43]. CFD, in particular, offers a robust tool for simulating real-world airflow patterns, while models such as the Wells–Riley equation have been instrumental in predicting airborne infection risks [44].

This chapter seeks to achieve three primary objectives: (a) understanding the dynamics of respiratory disease transmission in indoor environments, with a specific focus on COVID-19 transmission; (b) identifying effective methods for assessing IAQ; and (c) proposing strategies to enhance IAQ to reduce the spread of respiratory diseases, such as COVID-19. A key aim of this research is to ensure healthy indoor environments while balancing energy consumption considerations. To achieve these objectives, the following research questions are formulated:

State-of-the-Art Interventions

- What current state-of-the-art interventions are employed to mitigate the risk of indoor respiratory infections, with a specific focus on SARS-CoV-2, while concurrently improving IAQ?

Gaps and Limitations

- What are the existing gaps and limitations in current research endeavours aimed at designing measures to mitigate the risk of indoor respiratory infections?

Future Research Directions

- What potential future research directions should be pursued to sustain consistently safe indoor environments and proactively prevent the risk of respiratory viral infections?

By addressing these research questions, this study aims to offer valuable insights into the relationship between IAQ and respiratory disease transmission, with a particular emphasis on the challenges posed by COVID-19. The findings will contribute to a deeper understanding of current practices, limitations, and future research needs in the field.

The structure of this chapter mirrors the research questions. Following this introduction, Section 2 provides an overview of the methodology used in the literature review. Section 3 describes the transmission dynamics of respiratory viruses, particularly SARS-CoV-2, and evaluates existing interventions to mitigate the risk of infection in indoor spaces. Section 4 examines the gaps and limitations of current research, while Section 5 explores potential future research directions. Finally, Section 6 presents concluding remarks, summarizing the key findings and implications of the reviewed literature.

2.2 Literature Review Approach

This systematic review was conducted to identify and analyse contemporary research investigating the relationship between IAQ and the risk of respiratory infections in indoor environments. A comprehensive approach is required to fully understand how infections, particularly respiratory viruses, spread in enclosed spaces and how IAQ can be optimised. Key methods include epidemiological and microbiological studies, along with CFD simulations, to model airflow and particle behaviour. In addition, integrating digital technologies, such as Digital

Twins and IoT devices, has proven essential for managing indoor environments. These technologies facilitate virtual planning, real-time monitoring, and predictive maintenance, enhancing IAQ management capabilities.

Furthermore, the analysis of unstructured Big Data generated by IoT devices, combined with AI techniques such as ML algorithms, provides valuable insights for informed decision-making regarding IAQ. To achieve a comprehensive understanding of infection transmission in indoor environments, it is also necessary to consider a combination of engineering controls, protective measures, and behavioural theories. These approaches offer a well-rounded perspective, allowing for the analysis of the physical, behavioural, and protective aspects of indoor infection risks.

Table 2.1 summarises the various proportions of studies dedicated to each approach. The current research focuses on the transmission of respiratory viruses in indoor environments, particularly emphasising the transmission of SARS-CoV-2 and its airborne surveillance, engineering and nonengineering control strategies, CFD modelling, and energy consumption related to IAQ.

While numerous methods exist to investigate infection transmission and IAQ, this research focuses on SARS-CoV-2 due to its global significance and the unique challenges it presents as a public health concern. SARS-CoV-2 has driven a heightened interest in how to maintain optimal IAQ while reducing infection risks in indoor settings, such as office environments.

Figure 2.1 outlines the process by which relevant documents were sourced from established databases, including IEEE, Scopus, Web of Science, and ScienceDirect using the following keywords: [Indoor OR confined OR enclosed] AND [air quality OR ventilation OR CO2] AND [SARS-CoV-2 OR COVID-19 OR SARS OR respiratory viruses]. Initially, these keywords led to the identification of 2722 documents, including journal articles, review papers, and conference papers.

Category	**Percentage**	**Notes**
Epidemiological Modes	29.78%	CFD simulations were the focus of 10.67% of the total reviewed publications.
Microbiological Methods	44.38%	ML techniques were utilised in 5.06% of the microbiological methods studies.
Engineering and Protective Theories	25.84%	Energy consumption considerations were integral to 19.57% of the engineering and protective measures studies.

Table 2.1: The percentage of publications in each category

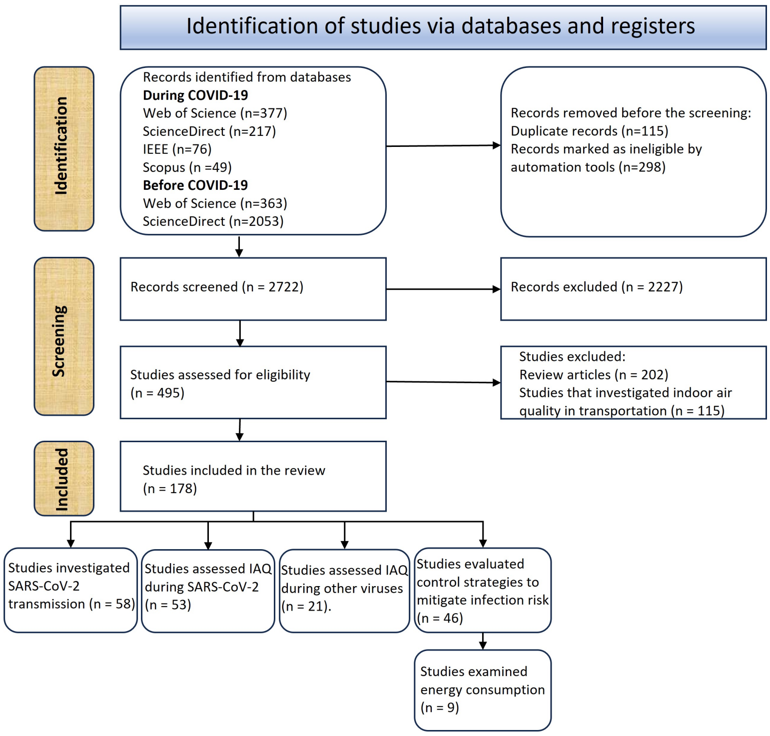


Figure 2.1: PRISMA flow diagram for systematic review

The systematic review was conducted through three primary steps:

1. Identifying authoritative research papers through established academic search

engines.

2. Screening and retaining relevant publications that met the research criteria.

3. Extracting relevant studies focusing on the transmission of COVID-19 and other respiratory viruses in relation to IAQ.

Figure 2.2 illustrates the significant increase in research publications on IAQ following the onset of the COVID-19 pandemic, highlighting the growing recognition of its importance. Figure 2.3 further categorises the literature, showing that most publications fall within the fields of environmental sciences, engineering, and public health, with a particular emphasis on occupational health. To ensure the relevance of the research, studies from prior years were included in the review if they demonstrated clear applicability to COVID-19.

In the initial review process, 115 duplicate articles and 298 ineligible publications (identified by automation tools) were excluded. After scanning titles and reading abstracts, the document count was reduced from 2722 to 495 papers. Following a more in-depth screening, 202 review papers and 115 papers focusing on IAQ in transportation settings were excluded, leaving 178 papers for further analysis.

From the updated collection of articles, four distinct themes emerged:

- Pre-COVID-19 indoor virus transmission: Investigating the spread of viruses in indoor environments before the emergence of COVID-19.

- SARS-CoV-2 transmission in indoor environments: Analysing the unique challenges posed by COVID-19, particularly its airborne transmission.

- IAQ assessments: Evaluating IAQ in various settings and its correlation with infection risks.

- Control strategies: Exploring both engineering and nonengineering interventions designed to mitigate infection risks in indoor environments.

These themes provide a structured overview of the diverse research areas explored in the literature, offering valuable insights into the evolving body of knowledge on IAQ and respiratory infection risks.

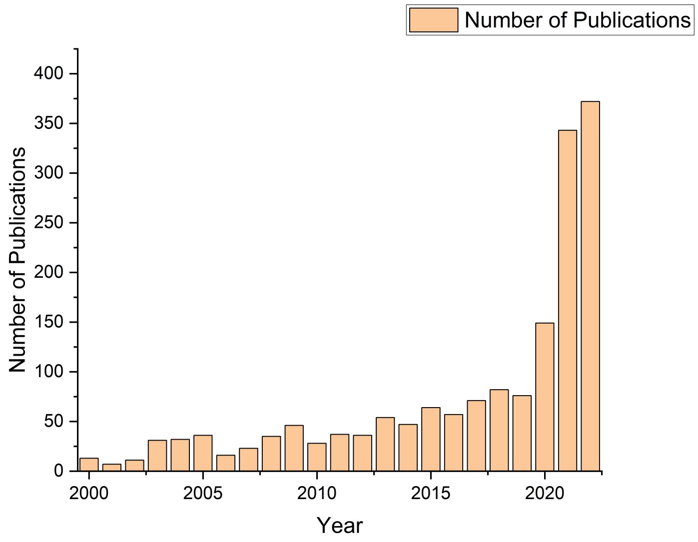


Figure 2.2: Number of IAQ documents based on the year of publication

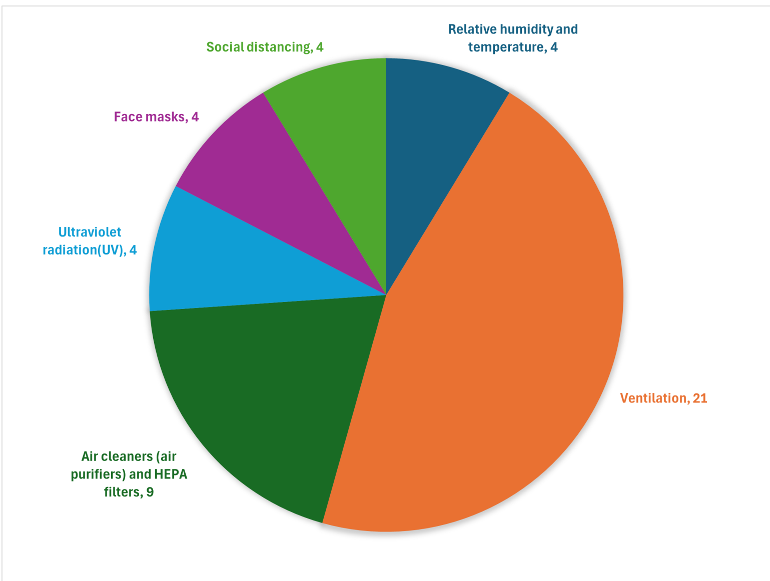


Figure 2.3: Publication categories

To systematically explore each theme, a framework was developed, guiding the analysis of studies based on the following key attributes:

1. Scale: Identifying the type of indoor environment analysed (e.g., office, residential, and healthcare settings).
2. Application field: Categorising studies by their specific research field (e.g., environmental science, engineering, and public health).
3. Scope: Summarising the overall objectives and research focus of each study.
4. The type of method utilised: This determines the method used to validate the study.
5. IAQ measurements: Assessing whether IAQ monitoring technologies, such as sensors, were employed to collect data.
6. Conclusions: Summarising the key findings and outcomes of each study.
7. Study limitations: Highlighting any constraints or limitations encountered in the studies, such as a limited focus on certain environmental factors or data reliability issues.
8. Future directions: Providing recommendations for future research, focusing on improving IAQ, and mitigating the transmission of airborne viruses in indoor environments.

This systematic approach to the literature review ensures a comprehensive understanding of current research trends and helps identify gaps and opportunities for future research aimed at improving IAQ and preventing the spread of respiratory viruses, particularly in the context of pandemics such as COVID-19.

2.3 Indoor Air Quality (IAQ) During and Before COVID-19

Respiratory viruses, including influenza, parainfluenza, RSV, severe acute respiratory syndrome coronavirus (SARS-CoV), rhinovirus, and adenovirus, are prominent human pathogens that primarily affect the upper respiratory tract. Since pandemics caused by respiratory viruses have the potential to cause widespread harm, public awareness and concern regarding their transmission has increased, particularly in the context of indoor environments[12]. These viruses typically spread through four primary transmission routes, as illustrated in Figure 2.4: direct contact (e.g., handshakes), indirect contact via fomites, respiratory droplets (particles >5 µm), and aerosols (particles <5 µm) [18–20]. Each of these routes presents unique challenges for controlling virus spread in enclosed spaces, emphasising the need for comprehensive IAQ management strategies.

In this section, as detailed in Table 3.1, we will review various studies investigating the transmission of respiratory viruses in indoor environments.

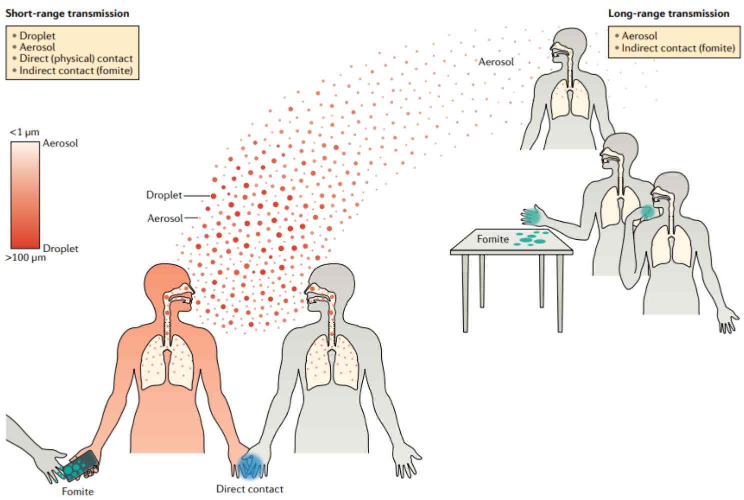


Figure 2.4: Major routes of respiratory viruses transmission [18]

2.3.1 Severe Acute Respiratory Syndrome

SARS, a coronavirus that emerged in China in the early 2000s, triggered a global outbreak that highlighted the challenges of controlling respiratory virus transmission in indoor environments [45]. Several studies have examined the transmission dynamics of severe acute respiratory syndrome (SARS) in indoor settings. For instance, [46] investigated the movement of air between apartments in high-rise buildings, noting the difficulty of controlling air leakage due to pressure differences and building airtightness. Similarly, Niu and Tung [47] provided insights into vertical transmission in high-rise buildings, where exhaust air was shown to travel between floors through window openings.

Further research explored engineering controls and public health interventions. For example, [48] assessed the effectiveness of isolation measures and contact tracing in controlling the SARS epidemic in hospitals and schools. Jiang et al. [49] emphasised the importance of maintaining safe ventilation rates in hospital settings to prevent viral transmission, a finding corroborated by Yu et al. [50] in their CFD studies on virus dispersion in healthcare environments.

2.3.2 Influenza

Influenza is another highly contagious respiratory virus that has historically affected both humans and animals. Influenza was declared a pandemic in 2009 by the World Health Organisation (WHO)[51] and has been the subject of numerous studies aimed at understanding its transmission dynamics and control measures. Chen et al. [48], Chen and Liao [52] explored the role of engineering controls, such as HVAC systems, in mitigating influenza transmission in schools and hospitals. Pantelic et al. [53] demonstrated the effectiveness of personalised ventilation (PV) in reducing infection risks in indoor environments.

Environmental controls have also been shown to impact influenza transmission.

Studies by Myatt et al. [54], Koep et al. [55], Noti et al. [56] reported that maintaining RH above 40% significantly reduces the survival of the influenza virus. Azimi and Stephens [57] highlighted the role of HVAC filtration systems in reducing influenza infection risk, noting that filtration was more cost-effective than increasing ventilation.

2.3.3 Middle East Respiratory Syndrome

Middle East Respiratory Syndrome (MERS), a coronavirus, emerged in Saudi Arabia in 2012, and is similar to SARS-CoV [58]. Several studies have investigated MERS transmission in indoor environments, particularly in hospitals, where infection control is paramount. Yu et al. [50], Sung et al. [59], Jo et al. [60] conducted CFD and tracer gas experiments to study airflow patterns in hospital wards, emphasising the role of airflow in infection control. Their findings suggest that increasing air exchange rates and improving ventilation system design can mitigate the risk of MERS transmission. Moreover, the influence of outdoor airflow on indoor infection risks was examined, revealing how external wind patterns can affect the movement of airborne pathogens inside buildings [60].

2.3.4 Other Respiratory Viruses

In addition to SARS, influenza, and MERS, other respiratory viruses, such as tuberculosis, measles, and adenovirus, have also been the subject of significant research. Chen et al. [48], Pantelic et al. [53], Beggs et al. [61], Wan et al. [62] highlighted the importance of combining environmental controls with public health interventions to reduce the transmission of these pathogens. For example, reducing waiting times in healthcare settings and minimising the number of susceptible individuals in shared spaces can significantly decrease the risk of airborne infections [61].

2.3.5 SARS-CoV-2 (COVID-19)

The most recent and impactful respiratory virus, SARS-CoV-2, originated in Wuhan, China, in late 2019 and rapidly spread worldwide, leading the WHO to a declare global pandemic. SARS-CoV-2, which is responsible for COVID-19, has posed unique challenges for indoor environments due to its persistence in aerosols and on surfaces. Studies such as [11] emphasised the importance of improved ventilation and air filtration in reducing the transmission of SARS-CoV-2 in enclosed spaces.

In addition to airflow and ventilation improvements, the effectiveness of interventions such as mask-wearing and social distancing has been extensively studied. [63] demonstrated that these measures significantly reduce transmission risks, while [64] explored how environmental factors, such as temperature and humidity, influence viral spread.

Ref	Building type	Type of respiratory virus	Result
[46]	Flat	SARS 2003	It is difficult to completely prevent the movement of air between the apartments in a high-rise building using only natural ventilation.
[47]	Flat	SARS 2003	Windows in high-rise buildings can be a significant pathway for the vertical spread of pathogen-containing aerosols.
[54]	House	Influenza	Increasing the RH level decreases influenza survival.
[48]	Hospital, elementary school	Influenza, Chickenpox, Measles, SARS 2003	Engineering control measures combined with public health interventions can effectively mitigate the spread of respiratory infections.
[49]	Hospital	SARS 2003	To minimise the risk of airborne viral infection, it is recommended to reduce air from a SARS patient by a factor of 10,000 by the introduction of clean air for safe ventilation.
[61]	Hospital	Influenza, Tuberculosis, Measles	To mitigate the infection risk spread in a waiting area, and before using expensive technological solutions, it is important to first minimise waiting times and the number of susceptible individuals present.
[62]	Hospital	Enterovirus, RSV, Influenza A virus, Adenovirus, M pneumoniae	All respiratory viruses except enterovirus were detected in the air and objects.
[50]	Hospital	MERS, SARS, and Influenza (H1N1)	The location of a virus-infected patient may affect the infection risk for others. In addition, increasing the air change rate can help reduce the risk of infection.
[59]	Hospital	MERS	Infectious aerosols may be spread indoors via airflow influenced by outdoor winds.
[60]	Hospital	MERS	Outdoor wind can spread infectious aerosols indoors through airflow.
[55]	School	Influenza	Increasing RH by up to 60% and increase absolute humidity (AH) may reduce influenza virus survival and transmission.
[52]	School	Measles, SARS 2003	The mathematical model used in this paper can offer an initiative applicable to a real elementary school to predict the optimal control measures and to protect susceptible students from infection by infected students.
[57]	Office	Influenza	Filtration reduces the infection risk of the influenza virus with lower costs than the option of increasing ventilation.
[56]	Chamber	Influenza	Keeping RH above 40% in indoor environments helps reduce the spread of the influenza virus.
[53]	Chamber	Influenza, Tuberculosis	The use of personal ventilation (PV) can reduce the infection risk of airborne transmissible disease.

Table 2.2: Publications investigating IAQ before COVID-19

2.4 Transmission Pathways of Respiratory Viruses

2.4.1 Transmission Vectors of SARS-CoV-2

SARS-CoV-2, the virus responsible for COVID-19, shares common transmission pathways with other respiratory viruses, such as influenza, SARS-CoV-1, and MERS-CoV. These transmission modes include direct contact, indirect contact via fomites, respiratory droplets, and aerosols. Among these, aerosol transmission has emerged as a significant vector, particularly in indoor environments characterised by poor ventilation and high occupant density. This mode of transmission has been extensively studied across various indoor settings, including educational institutions, healthcare facilities, offices, and public venues.

Aerosol transmission, whereby virus-laden particles smaller than 5 um remain suspended in the air for extended periods, is especially concerning in poorly ventilated indoor spaces. Numerous studies have demonstrated that SARS-CoV-2 can be transmitted via aerosols in confined environments, where the virus can persist in the air and be inhaled by occupants. Research on aerosol transmission in settings such as classrooms and educational buildings has revealed the potential for viral spread through an inadequate ventilation system [65–72]. Studies have also been conducted in healthcare facilities, where managing aerosol transmission is critical due to the high density of infected individuals [73–80]. Offices are another high-risk environment for aerosol transmission. Recent simulations and real-world measurements have indicated that inadequate air circulation and recirculation of air through HVAC systems can exacerbate the risk of airborne transmission [81–88]. Other settings such as nail salons [89], historic building [90], rooms [91–93], gyms [94], residential buildings [95], stores [96, 97], chambers [98], the Skagit Valley Chorale event [99], lift [100, 101], concert halls [102], restrooms [103], courtrooms [104], restaurants [105, 106], terraces [107], indoor arenas [108] and courtyards [109] have also been studied, highlighting the widespread relevance of aerosol transmission across different types of indoor environments.

In addition to aerosols, fomite transmission (i.e., the spread of infectious agents via contaminated surfaces) has been a subject of significant research in the context of COVID-19. Fomite transmission occurs when individuals touch surfaces contaminated with the virus and subsequently touch their face, allowing the virus to enter the respiratory system. Several studies have explored the potential for fomite transmission in hospitals, households, and public spaces, as outlined in Table 7.2. While some studies, such as Wang et al. [110], Viegas et al. [111], have reported negative results for SARS-CoV-2 on surfaces, likely due to routine cleaning and disinfection measures, other studies have detected the presence of viral particles in various indoor environments. For instance, [112–114] found SARS-CoV-2 RNA on hospital surfaces, with nine out of 37 samples testing positive. Similarly, [115] detected the virus in 25% of air and surface samples collected from hospitals. These findings highlight the potential for fomite transmission in high-risk environments, despite ongoing cleaning protocols.

In residential settings, [116] reported that 75% of surface samples collected from households tested positive for SARS-CoV-2, suggesting that fomite transmission remains a concern in environments where people share common surfaces and spaces. Similarly, [117] detected SARS-CoV-2 in both air and surface samples in residential buildings, further underscoring the importance of regular disinfection and airflow management in reducing transmission risks.

The next section will investigate the presence of SARS-CoV-2 in indoor environments by examining different surveillance techniques.

Ref	Building type	Sample size	Result reported in study
[110]	Hospital	45 samples	No SARS-Cov-2 RNA was detected among these samples.
[112]	Hospital	37 samples	Nine out of 37 samples tested positive for SARS-CoV-2.
[114]	Hospital	19 samples	SARS-CoV-2 was detected in the filters of the air filtration systems of COVID-19 wards.
[113]	Hospital	200 samples	50 samples out of 200 samples were positive for SARS-CoV-2.
[115]	Hospital	56 samples	25% of the samples tested positive for SARS-CoV- 2.
[116]	Households	13 samples	All air samples and 75% of the surface samples tested positive for SARS-CoV-2.
[111]	Educational building	106 samples	All the samples tested for SARS-CoV-2 were negative.
[117]	Residential building	7 samples	SARS-CoV-2 was detected in an air sample from volunteer A and in various air and surface samples from volunteer B.

Table 2.3: Information from publications on the SARS-COV-2 transmission through indoor surfaces in different indoor environments..

2.4.2 Airborne Surveillance of SARS-CoV-2

Detecting airborne viruses and evaluating IAQ require the application of diverse and precise techniques, such as air sampling and air monitoring. These methods are critical for understanding the presence and concentration of viral particles, particularly in environments where respiratory infections such as SARS-CoV-2 can spread via aerosols.

Air sampling, a widely used technique to identify airborne pollutants and pathogens in indoor environments, has been employed in numerous studies to detect the presence of SARS-CoV-2. These investigations, as summarised in Table 2.4, focus on a variety of indoor settings, including hospitals, households, and public buildings. For example, studies by Masoumbeigi et al. [118], Faridi et al. [119], Vosoughi et al. [120] reported negative results for SARS-CoV-2 in air samples collected from hospitals, likely due to effective ventilation and disinfection protocols. In contrast, other studies confirmed the presence of the virus in the air, particularly in high-risk environments such as hospitals, where infected individuals were concentrated [121–127]. Other studies have also detected SARS-CoV-2 in household air samples [116], public building [128], and residential building [117], suggesting that airborne viral transmission is not confined to healthcare facilities but can occur in a wide range of indoor environments, especially those with limited ventilation.

Indoor air monitoring is another critical tool for assessing the broader context of IAQ. It involves measuring a range of environmental factors, such as PM2.5 levels, CO2 concentrations, humidity, and VOCs as illustrated in Figure 2.5, all of which are relevant to understanding the potential for viral transmission. While some studies focus on one or two key IAQ indicators, others take a more comprehensive approach, as shown in Table 2.5 and Table 2.6.

PM2.5, in particular, has been the focus of several investigations into IAQ in households [129], apartments [130–132], restaurants [133], classrooms [134], and houses [135]. These studies demonstrate that elevated PM2.5 levels correlate with poorer air quality and increased health risks, including those related to respiratory viruses. Other key IAQ parameters, such asCO2, total volatile organic compounds (TVOC), NO2, and O3 have also been widely studied in relation to both air quality and potential viral transmission [136–144].

Further studies incorporate a wider range of environmental factors, including temperature, humidity (RH), and air velocity, providing a more holistic view of

IAQ [1, 142, 145–154]. Additionally, recent advancements in technology have enabled the use of IoT sensors and ML techniques to monitor and predict IAQ in real time. These technologies allow for more precise and continuous surveillance of IAQ, offering a proactive approach to managing indoor environments and ensuring healthy air quality [155–158]. The following sections investigate engineering and non-engineering control strategies.

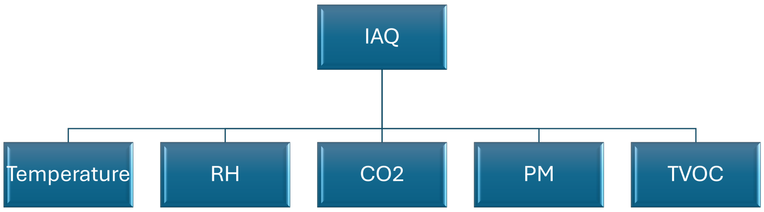


Figure 2.5: IAQ measurements

Ref	Building type	Sample size	Result reported in study
[118]	Hospital	31 samples	All the samples tested negative for SARS-Cov-2.
[119]	Hospital	10 samples	All the samples tested negative for SARS-Cov-2.
[120]	Hospital	33 samples	The results illustrated that air samples taken 2-5 metres away from the patient's beds were negative for SARS-COV-2.
[121]	Hospital	14 samples	Two out of 14 air samples tested positive.
[122]	Hospital	51 samples	Six of the 51 samples collected from the COVID-19 ward tested positive for SARS-CoV-2, four cases were in patient rooms, and two cases were in the hallway.
[123]	Hospital	16 samples	All samples from the toilets and hallway were negative, but two samples collected from the intensive care unit (ICU) were positive.
[124]	Hospital	107 samples	Six out of 107 air samples tested positive.
[125]	Hospital	13 samples	Five of the 13 air samples collected from three major hospitals in Kuwait tested positive for SARS-CoV-2.
[126]	Hospital	52 samples	Five out of 52 air samples collected from hospitals in Brazil tested positive for SARS-CoV-2.
[127]	Hospital	36 samples	Thirteen of the 36 cases tested positive for SARS-CoV-2.
[116]	Households	16 samples	All air samples and 75% of the surface samples tested positive for SARS-CoV-2.
[128]	public buildings	12 samples	Six out of 12 aerosol samples were detected for SARS-CoV-2.
[117]	Residential building	7 samples	SARS-CoV-2 was detected in an air sample from volunteer A and in various air and surface samples from volunteer B.

Table 2.4: Information from publications on the SARS-COV-2 transmission through indoor air in different indoor environments..

Ref	**Building type**	**Mean T (°C)**	**Mean RH (%)**	**Mean CO2 (ppm)**	**Mean PM2.5 (μg/m^3)**	**Mean PM10 (μg/m^3)**	**Mean TVOC(ppb)**
[137]	House	20 - 27	<50	1200-5000	12–25	20 - 50	-
[129]	House	12.4 - 17	-	-	62 - 142	-	-
[139]	House	24.6	52.8	-	5.6–12.2 in offices, 11.2–45.7 at homes	-	-
[136]	Apartment	Before lockdown 22.5-26, during lockdown 23.1-26	around 40	Before lockdown 731 - 2136.8, during lockdown 798.6 - 2395.7	before lockdown 10.63 - 16.07, during lockdown 7.19 - 16.94	-	before lockdown 272.524 - 5550.11, during lockdown 15.285 - 748.88 ppb
[138]	Apartment	20 - 30	45 - 50	470 - 2116	10 - 15	-	131 - 584
[131]	Apartment	NA	NA	396 for kitchen, 551 for bedroom, and 505 for hall	1465 - 247 in kitchen, 1151 - 160 in bedroom, 1565 - 166 in hall	94 in kitchen, in bedroom, 62 in hall	-
[134]	University	22.4-26	20.4-42.4	-	29 - 41	30 - 42	-
[154]	University	23.1	60	464.7	-	-	66.9
[1]	School	18 - 23.1	36.8 - 57.3	604 - 1079	-	-	-

Table 2.5: Mean values of IAQ measurements.

Ref	Building type	Mean T (°C)	Mean RH (%)	Mean CO2 (ppm)	Mean PM2.5 ($\mu g/m^3$)	Mean PM10 ($\mu g/m^3$)	Mean TVOC(ppb)
[150]	School	-	-	720.7 - 1325	-	-	-
[153]	School	19 - 21	42 - 50	553 - 700 ppm	25 - 48	38 - 81	-
[142]	School	7.8 - 10.7	35.4 - 46	577-2232	4.8-15.3	5.8 - 17.4	287-485
[141]	Secondary school and university	18.2 - 19.3	51 - 57	97 - 220	-	-	-
[149]	Kindergarten	before COVID-19 is 22.0775, during COVID-19 is 21.955 ○C	before COVID-19 is 33.32 , during COVID-19 is 31.125	before COVID-19 is 1221.88 and during COVID-19 is 847.12	-	-	-
[144]	Daycare centre	23.6 for nursery Room, 22.3 for activity Room	32.3 for nursery Room, 34.6 activity Room	648.1 for nursery Room, 608.3 for activity Room	9.1 for nursery Room, 6.3 for activity Room	16.4 for nursery Room,10.8 for activity Room	158.9 for nursery Room,158.6 for activity Room
[140]	Hotel	-	-	452.21 - 459.92	4.09 - 9.33	-	108.4 - 162.41
[133]	Restaurant	19.4-23.8	45-54	-	113.1 for the entire week	is 548.1 for the entire week	-
[135]	Residential, Industrial buildings	-	-	-	pre-lockdown 24 - 32 , during lockdown the hourly indoor PM2.5 concentrations 3 - 47	pre-lockdown 62 - 78 , during lockdown the hourly indoor PM10 concentrations 26 - 100	-

Table 2.6: Mean values of IAQ measurements.

2.5 Mitigation Strategies in Indoor Environments

Mitigating the airborne transmission of infectious pathogens, particularly in indoor environments, is a priority for public health. The key to effective mitigation lies in controlling the concentrations of respiratory aerosols, which can be achieved through both engineering and nonengineering strategies. Engineering strategies include manipulating indoor humidity and temperature, optimising ventilation systems, employing air filters, and utilising ultraviolet (UV) radiation for disinfection. Nonengineering strategies such as the use of face masks and maintaining physical distancing also play pivotal roles in minimising transmission risks. Figure 2.6 presents an overview of the academic literature concerning different control measures, indicating that ventilation is the most widely researched approach, with 21 studies emphasising its importance. Other strategies, including air cleaners, humidity control, UV radiation, face masks, and social distancing, have received comparatively less attention, with fewer than 10 publications focusing on each of these methods.

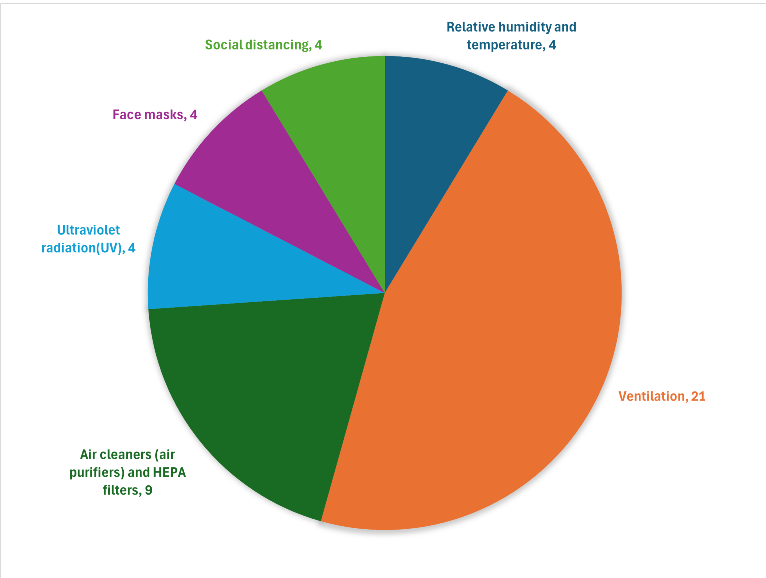


Figure 2.6: Distribution of research publications by IA control strategy

2.5.1 Humidity and Temperature Control

Controlling indoor RH and temperature is a crucial factor in reducing viral viability and transmission in indoor settings. The maintenance of optimal conditions significantly influences the survival and transmission of airborne viruses. Studies have shown that maintaining temperatures between 20°C and 25°C and RH levels between 40% and 50% significantly reduces the stability of airborne viruses, including SARS-CoV-2 [64, 159]. Conversely, conditions outside this range, such as humidity levels below 40% or temperatures above 30°C, might effectively reduce COVID-19 transmission [160, 161]. For influenza viruses, studies reveal that at 5°C, transmission showed high efficiency, while it was blocked or less effective at 30°C. Additionally, dry conditions (20% and 35% RH) were observed to be more conducive to spread compared to conditions with intermediate (50% RH) or high humidity (80% RH) [162, 163]. In conclusion, previous research underscores the importance of maintaining a RH range of 40% to 60% for optimal human health in indoor environments [159]. Table 5.3 outlines the environmental conditions required for the stability and inactivation of various viruses.

Ref	Type of virus	Stable at RH (%)	Mitigated at RH (%)	Stable at T (°C)	Miti-gated at T (°C)	Description
[17]	SARS 2003	40	-	21-23	-	The decay rates of SARS-CoV-2 and SARS-CoV-1 in aerosols exhibited similarities.
[64]	SARS 2003	40-50	-	20-25	-	Maintaining temperatures between 20°C and 25°C and RH levels between 40% and 50% was found to have a protective impact on the viability of airborne SARS-CoV and MERS-CoV.
[164]	SARS 2003	40-50	>95	22-25	38	SARS-CoV has been found to remain viable for a duration of up to five days at temperatures ranging from 22°C to 25°C and RH levels of 40% to 50%. It was found that increased temperature and humidity led to a rapid decline in viability.
[165]	Influenza	-	90	-	20	Based on experimental and simulated findings, 90% RH together with 20°C is recommended in an indoor environment to improve the prevention of influenza transmission.
[162]	Influenza	20 - 30	80	5	30	It was found that lower relative humidities ranging from 20% to 35% were highly conducive to transmission, whereas transmission was entirely halted at a high RH of 80%. Additionally, when guinea pigs were housed at 5°C, transmission occurred more frequently compared to 20°C, while at 30°C no transmission was observed.
[163]	Influenza	20 - 30	50-80	5	30	At 5°C, transmission showed high efficiency, while it was blocked or less effective at 30°C. Additionally, dry conditions (20% and 35% RH) were observed to be more conducive to spread compared to conditions with intermediate (50% RH) or high humidity (80% RH).
[64]	MERS	40-50	-	20-25	-	Maintaining temperatures between 20°C and 25°C and RH levels between 40 and 50 was found to have a protective impact on the viability of airborne SARS-CoV and MERS-CoV.
[166]	MERS	40	-	20	-	At a temperature of 20°C and a RH of 40%, MERS-CoV was a very stable aerosol.
[167]	MERS	-	-	25	38	The efficiency of MERS inactivation was significantly higher at a temperature of 38°C compared to 25°C.
[17]	SARS-CoV-2	40	-	21-23		The decay rates of SARS-CoV-2 and SARS-CoV-1 in aerosols exhibited similarities.
[159]	SARS-CoV-2	<40	40-60	-	-	Previous research indicates that a RH range of 40–60% was found to be optimal for human health in indoor settings.
[160]	SARS-CoV-2	<40 and >80	<70	-	-	The transmission of the virus is not significantly affected by temperature. However, it is recommended that a safe humidity level be below 70% RH.
[161]	SARS-CoV-2	-	<78	-	30	Maintaining a mean RH below 78% and continuous daily temperatures above 30°C significantly reduce transmission.

Table 2.7: Environmental conditions for the stability and inactivation of various viruses..

2.5.2 Ventilation Strategies

Ventilation is one of the most critical engineering strategies for mitigating infection transmission in indoor spaces. It plays a central role in maintaining IAQ by diluting and removing airborne contaminants, including viruses. Ventilation can be provided through mechanical systems, natural forces, or a combination of both. Research on natural ventilation has explored its effectiveness in various settings[46, 47, 168–175]. Mechanical ventilation systems, on the other hand, have been studied in different spaces[63, 176–184]. Mixed ventilation systems, which combine mechanical and natural ventilation, have also demonstrated success in improving IAQ while minimising energy consumption[185–187].

2.5.3 Air Cleaners and High-efficiency Particulate Air Filters

Air cleaners, particularly those equipped with HEPA filters, are another effective strategy for reducing the concentration of airborne pathogens in enclosed spaces. Studies have shown that placing air purifiers near infected individuals significantly reduces viral aerosol concentration He et al. [188], Narayanan and Yang [189]. HEPA filters, in particular, have proven to be highly effective in poorly ventilated spaces. For instance, in dental treatment rooms, HEPA filters dramatically reduced aerosol accumulationRen et al. [190]. Other studies confirmed that while HEPA systems may increase noise levels, they provide substantial benefits by reducing aerosol transmission in environments with limited ventilation Bluyssen et al. [191]. Additionally, Lelieveld et al. [192] highlighted that the use of HEPA filters could potentially reduce individual infection risk by a factor of 5 to 10, affirming their critical role in controlling airborne viruses.

2.5.4 Ultraviolet Radiation

UV radiation, particularly UV-C light, has been widely recognised for its ability to inactivate airborne pathogens, including SARS-CoV-2. Recent studies have demonstrated that integrating UV-C disinfection with ventilation systems can significantly reduce airborne virus concentrationsFeng et al. [193], Srivastava et al. [194]. Kahn and Mariita [195] highlighted the importance of balancing UV-C intensity with airflow to optimise infection control. UV-C radiation is especially effective when applied in high-risk areas such as hospitals and intensive care units (ICUs), where maintaining sterile air conditions is critical. In line with these results, de Souza et al. [196] successfully used UV germicidal irradiation in an ICU's HVAC system, pointing out how important it is for keeping the air clean, especially when the UV system is always on.

2.5.5 Masks and Social Distancing

Face masks and social distancing are among the most effective nonengineering strategies for reducing infection risks in indoor environments [89]. Numerous studies have shown that face masks, particularly those with high filtration efficiency such as N95 masks, can significantly reduce the likelihood of airborne transmission Lelieveld et al. [192], Shen et al. [197]. Coyle et al. [63] found that masks when combined with other strategies, such as HEPA filtration and enhanced ventilation, offer comprehensive protection against viral transmission. Social distancing, particularly maintaining a distance of at least 1 meter, has been shown to reduce transmission risk in various indoor settings, including schools [142, 145], hospitals [146], elevators [100], a high-rise institutional building [181], and the Lawrence Berkeley National Laboratory [72].

In conclusion, effectively mitigating SARS-CoV-2 transmission in indoor environments necessitates implementing several key strategies. First, maintaining indoor temperatures between 20°C and 25°C and RH levels between 40% and 50% is essential for reducing the viability of the virus. Second, optimising ventilation systems is critical to balancing air quality and energy efficiency, emphasising increasing air exchange rates to dilute and remove airborne contaminants. Additionally, HEPA filters and UV-C radiation have proven to be highly effective for air purification, with UV-C being particularly beneficial when integrated into HVAC systems. Furthermore, the use of face masks, especially those with high filtration efficiencies, such as N95 masks, plays a vital role in personal protection, reducing transmission risks by up to 99%. Maintaining a physical distance of at least 1 meter in social settings also significantly decreases the risk of viral spread. When these strategies are combined, they form a comprehensive framework for minimising COVID-19 transmission in various indoor settings, providing actionable insights for enhancing future health and safety protocols.

The next section will explore transmission modelling, utilising CFD and other numerical modelling techniques to enhance our understanding of pathogen spread in enclosed spaces.

2.6 Modelling Transmission Using Computational Fluid Dynamics and Numerical Modelling

In addition to real-time air monitoring, computational models offer a powerful alternative for assessing the risk of infectious disease transmission. CFD models, which utilise numerical analysis to simulate fluid flow and the dispersion of airborne contaminants, are widely employed to understand how infectious agents travel within indoor environments. These models can simulate the behaviour of airborne particles under varying environmental conditions, allowing for the prediction of infection risks without the need for real-world case studies. Many of the studies reviewed in this systematic analysis have applied CFD models, either independently or in conjunction with experimental data, to simulate airflow patterns and evaluate the movement of airborne particles in a range of indoor settings[49, 50, 60, 77, 79, 90, 97, 107, 182, 198, 199]..

For instance, in a study by Mirzaei et al. [200], an Eulerian CFD model was validated against experimental data and then combined with a Lagrangian CFD model to simulate the trajectory and evaporation of droplets of varying sizes. This hybrid approach allowed for a comprehensive analysis of how droplets behave in indoor air. Similarly, Barbosa and de Carvalho Lobo Brum [186] used multizone-CFD software developed by the National Institute of Standards and Technology to assess different ventilation modes, filter efficiencies, and outdoor air flow rates. This study highlighted the versatility of CFD in evaluating various IAQ solutions.

Another important contribution comes from [176], who modelled the role of HVAC systems in the diffusion of contagion in a hospital setting through CFD simulations of cough dispersion. Garbey et al. [73] applied CFD to test the components of a hybrid stochastic compartment model, simulating airborne particle transport in a surgical suite over a year. Their long-term analysis provided valuable insights into how airborne pathogens move in controlled environments.

Shang et al. [88] conducted transient CFD simulations to assess infection risks under varying conditions, such as calm and windy scenarios, demonstrating the importance of environmental factors in viral transmission. Moritz et al. [108] simulated aerosol dispersion from 4,000 virtual participants using CFD, which offered a large-scale understanding of how aerosols behave in crowded environments.

In Feng et al. [193], computational fluid-particle dynamics (CFPD) was employed to simulate the generation, transmission, and clearance of airborne droplets containing SARS-CoV-2 under various ventilation and UV air cleaning conditions. This model provided insights into the efficiency of UV-C air cleaners in reducing airborne viral loads in COVID-19 patient rooms.

Moreover, Dong et al. [201] integrated CFD with the Wells–Riley model to calculate the infection rate distribution in an indoor space, combining fluid dynamics with probabilistic infection models to offer a more nuanced understanding of infection risk. Sarhan et al. [202] used a 3D CFD model to simulate human respiration activities, including breathing and speaking, within indoor spaces, providing detailed insights into the dynamics of respiratory droplet dispersion.

These CFD models have proven invaluable in understanding airflow patterns, droplet dispersion, and the effectiveness of ventilation, filtration, and air-cleaning strategies. By providing detailed visualisations and quantitative data, CFD allows researchers and engineers to design more effective interventions to reduce the transmission of airborne diseases, particularly in high-risk indoor environments, such as hospitals, offices, and schools.

It is essential, however, to balance IAQ improvements with energy consumption because enhanced ventilation and air purification systems can significantly impact building energy efficiency. The following section will explore the relationship between IAQ improvement measures and their associated energy implications.

2.7 Energy Consumption

Improving IAQ while managing energy consumption presents a significant challenge in creating sustainable and healthy indoor environments. Many strategies designed to mitigate infection risks, such as increased ventilation, advanced filtration systems, and air purifiers, can significantly impact energy use. Achieving a balance between optimising IAQ and minimising energy consumption is critical, particularly in the context of long-term sustainability and operational efficiency.

Numerous studies have explored this balance, assessing how IAQ interventions affect energy usage. Risbeck et al. [203] developed dynamic models to evaluate airborne transmission risk and energy consumption in HVAC systems, factoring in controller setpoints and weather forecasts. Their results demonstrated varying infection risks and identified energy-efficient disinfection strategies based on location-specific conditions.

In a similar vein, Schibuola and Tambani [204] investigated high-efficiency systems designed to contain COVID-19 through increased ventilation rates. Their study demonstrated that employing an autonomous high-efficiency air handling unit (HEAHU) reduced energy consumption by 60% to 72% while maintaining effective IAQ. In a follow-up study, the authors compared the performance of an exhaust air heat pump (EAHP) and a heat recuperator under various climatic conditions, emphasising that HEAHU provided energy savings between 31% and 46%, whereas EAHP savings ranged from 2.5% to 48%. In milder climates, EAHP slightly outperformed HEAHU [205].

Saikia et al. [206] designed a resource-efficient healthcare ward, finding that excessive cooling energy could increase energy costs while reducing productivity, highlighting the need for resource-conscious HVAC design. Similarly, Ascione et al. [207] assessed the energy impacts of higher mechanical ventilation rates and microclimatic control within buildings, concluding that while increased outdoor air led to higher energy demands, it also significantly improved IAQ.

Smart control systems are another approach to balancing IAQ and energy consumption. [208] proposed a smart ventilation system that adjusts ventilation rates based on real-time occupancy, resulting in energy savings of 11.7% and a 2% reduction in infection risk. Similarly, Aliero et al. [209] developed a smart sensing framework for indoor occupancy that has the potential to save up to 50% of energy by optimising HVAC operation based on real-time usage data.

Innovative solutions combining natural and mechanical ventilation have also been explored. Aviv et al. [210]) introduced a hybrid HVAC model that works alongside natural ventilation to reduce infection risk and energy consumption simultaneously. Similarly, Rey-Hernández et al. [185] examined hybrid ventilation systems with heat exchangers, finding that they met IAQ standards for 70% of operating time, while significantly reducing energy consumption and carbon emissions.

In high-rise buildings, Sha et al. [181] demonstrated that optimising mechanical ventilation systems could reduce energy consumption by up to 40%, while maintaining safe IAQ levels to minimise COVID-19 transmission risks.

Finally, de Frutos et al. [211] analysed the impact of quarantine on energy consumption and IAQ within 12 residences in Madrid, finding that household composition, habits, and daily activities significantly influenced both energy use and indoor environmental quality.

These studies underscore the importance of integrating energy-efficient solutions into IAQ management strategies. Whether through advanced HVAC systems, smart controls, or hybrid ventilation approaches, the goal is to maintain optimal IA while minimising energy costs.

The following section will outline gaps and limitations identified throughout the literature, providing a framework for future research in balancing IAQ and energy efficiency.

2.8 Thermal Comfort Standards

Establishing a well-balanced thermal environment is fundamental to enhancing occupant comfort, health, and productivity within buildings [212]. TC is broadly defined as the state of mind in which a person expresses satisfaction with the surrounding thermal conditions [213]. In practice, this means creating indoor environments where the majority of occupants feel neither excessively warm nor too cold. To achieve this consistently, comprehensive standards have been developed by international and national bodies, providing designers and engineers with objective criteria to evaluate and maintain IEQ. Although these standards aim to ensure safe, healthy, and productive spaces, they may sometimes fall short of addressing individual variations, which can lead to occupant dissatisfaction [214].

2.8.1 ASHRAE 55 Standard

The ASHRAE Standard 55 is one of the most widely adopted guidelines for TC. Originally published in 1966 and updated in subsequent years (1974, 1981, 1992, 2004, 2010, 2013, and most recently in 2017) [215], it specifies the combinations of environmental and personal factors (e.g., metabolic rate, clothing insulation, air temperature, radiant temperature, air velocity, and RH) that yield thermally acceptable conditions for most occupants [216]. The standard defines two acceptability levels (80% and 90%) that determine the operating temperature ranges. Although it is grounded in Fanger's predictive mean vote (PMV) model [23], ASHRAE 55 is designed to be adaptable, incorporating data from a wide range of climates, as demonstrated by its application in countries such as Chile [217] and Spain [218]. The model also sets specific prerequisites, such as the absence of active HVAC systems, metabolic rates between 1 and 1.3 met, and the possibility for the occupants to adjust their clothing insulation between 0.5 and 1 clo, and generally recommends maintaining indoor temperatures between 20°C and 26°C with RH between 30% and 60% [219, 220].

2.8.2 European Standards: EN 15251 and EN 16798-1

In Europe, the adaptive approach emerged through EN 15251:2007, which was grounded in the Smart Controls and Thermal Comfort (SCATs) project [221]. Unlike ASHRAE's two categories, EN 15251:2007 defines three categories that are tailored to occupant expectations and building types:

- **Category I:** Spaces designed for occupants with reduced adaptive capacity (e.g., the elderly or infirm).

- **Category II:** New buildings.
- **Category III:** Existing buildings.

EN 15251:2007 aligns with ASHRAE 55 in prescribing certain prerequisites, namely buildings without mechanical HVAC, occupant metabolic rates from 1.0-1.3 met, and flexible clothing insulation from 0.5-1.0 clo [222]. The standard further requires that mean daily outdoor temperature be 15°C to 30°C for lower-limit considerations and 10°C to 30°C for upper-limit determinations. More recently, EN 16798-1 reaffirms these adaptive concepts, specifying comfort ranges of 20°C to 24°C in winter and 23°C to 27°C in summer, with 30–70% RH recommended. EN 16798-1:2019 refines these recommendations further by establishing seasonal comfort ranges, such as operative temperatures of 20°C to 24°C in winter and 23°C to 27°C in summer, along with a RH range of 30% to 70% [222].

2.8.3 ISO 7730 Standard

First introduced in 1984 and later revised in 1994 and 2005 [223], ISO 7730 incorporates the Fanger comfort model into its framework by providing the equations needed to calculate both the PMV and the PPD occupants. This standard not only assesses overall thermal conditions but it also offers methodologies for addressing local discomfort issues, such as those caused by asymmetric radiation, draughts, and vertical temperature gradients. The latest version categorises comfort levels based on varying PPD thresholds and includes guidance on adjusting air speed to compensate for increases in operative temperature. However, it does not integrate the adaptive comfort approach. Typical recommendations under ISO 7730 include indoor temperature ranges of 18°C to 23°C during winter and 22°C to 27°C during summer [224].

2.8.4 Integrative Analysis and Limitations

Collectively, these standards aim to maintain a PMV value between -0.5 and 0.5—a range widely accepted as ensuring adequate TC for most occupants [216, 225]. Although they provide a robust framework for the design and evaluation of indoor environments, the prescriptive nature of these guidelines may not fully account for individual differences or dynamic environmental conditions. This discrepancy can sometimes lead to a gap between standardised comfort levels and the actual experiences reported by occupants. Recognising and addressing these limitations is crucial for advancing TC research and practice.

2.9 Research Gaps

This systematic review offers a comprehensive analysis of strategies aimed at mitigating infection risks and improving IAQ. Despite extensive research on COVID-19 transmission, IAQ, and energy consumption optimisation as discussed in sections 2.3 to 2.5 and 2.7, several gaps and limitations remain. These gaps hinder a comprehensive understanding of IAQ dynamics and present challenges to the effective implementation of interventions.

2.9.1 Lack of Air and Surface Samples

Air and surface samples play a critical role in assessing microbial contamination and monitoring IAQ. Despite several studies focusing on IAQ in environments such as hospitals, the majority rely on small sample sizes, which limits their generalisability [116, 117]. Additionally, there is a notable lack of research examining IAQ in diverse indoor settings, such as higher education buildings. These environments, which serve both as workplaces and learning spaces, require specialised study. Only one of the reviewed studies has investigated IAQ in higher education settings, which highlights the need for broader sampling and context-specific IAQ assessments[111].

2.9.2 Inadequate Consideration of Occupancy Patterns and Behaviour

The influence of occupants on IAQ is a crucial factor that is often overlooked in research. Indoor environments are dynamic, with occupancy levels, activities, and movement patterns significantly impacting air quality. Studies that neglect to account for these variables, such as experiments conducted in nonoccupied settings, risk yielding results that do not reflect real-world conditionsPark et al. [172]. Moreover, assumptions of uniform occupancy distribution fail to account for the uneven movement and congregation of individuals, which can affect pollutant dispersion and ventilation efficiencySinger et al. [72], Li and Tang [179].

2.9.3 Insufficient Monitoring of Indoor and Outdoor Environmental Parameters

Accurate IAQ assessments require key parameters such as temperature, RH, and CO2 levels, both indoors and outdoors to be monitored. However, many studies fall short by making assumptions that overlook the dynamic nature of these variables. For instance, Cammarata and Cammarata [83] assumed constant indoor temperature and RH, neglecting the natural fluctuations that occur in real-world settings. Similarly, important factors such as humidity variations and the effect of open doors on IAQ have often been ignored, leading to potential biases[97, 226].

Additionally, many studies fail to measure outdoor environmental factors such as temperature, RH, and wind speed, which limits a comprehensive understanding of how outdoor conditions affect IA. The omission of seasonal variations further reduces the depth of IAQ analyses. In studies that assess the impact of outdoor particles and occupant activities on IA, inconsistencies and missing data complicate the interpretation of results. Variations in outdoor particle concentrations and challenges in simultaneous data collection add further complexity[130].

2.9.4 Shortage of Evaluation and Simulation Studies

Although numerous studies have evaluated IAQ during the COVID-19 pandemic, several gaps remain in terms of evaluation and simulation methodologies. One key limitation is the focus on short work hours, which overlooks IAQ dynamics over longer periods, such as full workdays. This limits our understanding of air quality fluctuations throughout the day and hinders the development of comprehensive IAQ guidelinesMotamedi et al. [182].

Additionally, many studies fail to account for climate variations in IAQ assessments, despite the significant impact that different climatic conditions can have on air quality[145]. There is also a need for more in-depth research on infection transmission, particularly for viruses such as SARS-CoV-2, using tools such as CFD and airflow modelling[1].

Another overlooked factor is the influence of furniture on airflow patterns, which can significantly affect pollutant dispersion and ventilation effectiveness. Many studies do not consider this aspect, which limits the realism of their findings[182].

Finally, while IAQ guidelines exist in certain regions, there is a lack of region-specific guidelines for areas such as Saudi Arabia. Developing localised IAQ standards is crucial for addressing the unique environmental and cultural factors that affect air quality [131].

2.9.5 Neglect of Critical Factors Influencing Ventilation System Performance

Effective ventilation, whether natural or mechanical, is essential for improving IA and reducing infection risks. However, many IAQ studies overlook critical conditions that significantly influence ventilation performance, such as aerosol circulation caused by infected individuals in enclosed environments[90]. Ignoring these factors can lead to incomplete insights into how ventilation systems manage airborne transmission, which limits the real-world applicability of IAQ guidelines.

Additionally, variations in simulation parameters, particularly boundary conditions, can greatly affect study outcomes. In particular, changes to HVAC systems, such as vent positions or airflow rates, can make findings less generalisable across different indoor environments[79]. The adaptability of IAQ guidelines to different HVAC configurations and setups is essential to ensure their relevance and effectiveness across diverse indoor spaces.

2.9.6 Energy Consumption and Cost

While extensive research has focused on infection transmission risks, there is a significant gap in the literature regarding the analysis of energy consumption, noise, initial investment, and overall cost in the context of IAQ improvements. This lack of comprehensive evaluation limits our understanding of the practicality and sustainability of various IAQ enhancement strategies. Most studies focus on mitigating infection risks but have often overlook the long-term viability and environmental impact of the proposed solutions[68].

Additionally, the absence of simulations involving heat recovery techniques, particularly in winter, is a key oversight. The effectiveness and cost-efficiency of IAQ strategies, especially in colder climates, can be significantly influenced by integrating heat recovery mechanisms [181]. Addressing these factors is essential for a holistic understanding of IAQ interventions and their energy implications.

2.9.7 Air Quality Based on Dynamic Data

Many previous studies on IAQ were conducted in small indoor environments with few or no occupants to avoid the complexities of data collection in larger spaces. While some research has focused on larger environments, these studies primarily relied on simulations without incorporating real-time aerosol particle data, accurate IAQ metrics, or building operational data. The absence of outdoor air quality measurements further limits the ability to accurately assess the contribution of external pollutants to IA, particularly in environments such as classrooms [153].

2.9.8 Digital Twin Model and Machine Learning Models

Digital Twins enable the creation of a dynamic, virtual replica of an indoor environment that synchronises with real-world conditions via sensor inputs. This capability is especially valuable in the context of IAQ and airborne infection control, as it allows for the simulation, prediction, and optimisation of ventilation performance, occupant exposure, and system responsiveness under various scenarios — something traditional static models cannot achieve.

There is a notable gap in the development of a unified model for different indoor environments that integrates DTs with machine learning (ML) to support nonexperts in decision-making. Furthermore, few studies have explored the predictive capabilities of ML to estimate thermal comfort or pollutant concentrations. ML has the potential to simulate complex multi-variable scenarios, offering real-time, low-cost insights with minimal environmental burden.

Several studies have explored IAQ monitoring and forecasting using ML. For instance, Sharma et al. [156] proposed IndoAirSense, a low-cost IAQ estimation model using long short-term memory (LSTM-wf) in university classrooms. Mumtaz et al. [155] introduced an IoT-based platform for monitoring indoor contaminants using ML. Similarly, Marzouk and Atef [158] employed continuous IoT monitoring in educational buildings, using deep learning to analyse relationships among air quality variables. Taheri and Razban [157] developed a dynamic CO2 model to forecast concentrations over time using ML.

However, these studies share a common limitation: none of them incorporated a DT model to enable continuous synchronisation with the physical environment. The lack of a real-time, bidirectional feedback loop between data, prediction, and system control restricts their responsiveness. Moreover, the application of ML for infection risk prediction or outbreak forecasting remains largely unexplored.

2.9.9 Infection Transmission in Indoor Environments

Future research must deepen the understanding of respiratory virus transmission dynamics, particularly in relation to the interactions between direct and indirect contact, respiratory droplets, and aerosols across various indoor settings[18–20]. Tailored infection control strategies should be developed for specific environments, such as schools, hospitals, offices, and gyms, each requiring unique ventilation and air quality management optimisation.

Research on high-rise buildings, for instance, must focus on air leakage, spatial positioning, and ventilation rates, drawing lessons from previous epidemics[46, 47]. The role of outdoor factors, such as wind influence on indoor air dispersion, should also be prioritised in designing adaptive infection control measures[60].

A holistic approach that addresses multiple respiratory viruses is needed to identify common principles for broad-spectrum control measures. Real-time monitoring systems are essential to maintaining continuous vigilance, particularly in high-touch environments. In addition, research should explore the psychological impacts of prolonged preventive measures and how behavioural interventions can be effectively implemented to promote compliance [113, 114, 116, 117].

Dynamic CFD models that incorporate human movement and real-world variables can significantly enhance the accuracy of airflow and infection risk simulations. Sustainability considerations must also be integrated into these strategies to minimise environmental impact without sacrificing effectiveness. Finally, fostering cross-disciplinary collaboration among epidemiologists, engineers, psychologists, and environmental scientists is crucial to the development of innovative, comprehensive solutions for managing indoor transmission risks.

2.9.10 Indoor Air Quality Factors

Future research on IAQ should embrace a multifactorial approach, expanding monitoring beyond individual parameters such as CO2, PM, RH, and temperature. A holistic assessment should consider the complex interactions between pollutants and environmental factors. Special emphasis should be placed on educational buildings, which require tailored IAQ strategies due to their high occupancy and unique characteristics. Integrating outdoor conditions into IAQ assessments is also crucial to understand the influence of external pollutants on IA.

Advances in IAQ monitoring technologies, such as the development of Digital Twins for real-time, continuous monitoring, can significantly enhance IAQ management. Additionally, applying ML algorithms to predict and mitigate infection risks presents a promising research direction, particularly for managing airborne diseases such as COVID-19. These multifaceted approaches aim to deepen our understanding of IAQ, especially in educational settings, and foster the development of advanced monitoring and predictive models for comprehensive IAQ management.

2.9.11 Nonengineering Control Strategies

While nonengineering interventions, such as face masks and social distancing, have proven to be effective in reducing infection risks, future research should focus on optimising these measures for enhanced safety and user comfort. Exploring alternative materials and designs for masks, especially in addressing health risks associated with prolonged use, could significantly improve the mask-wearing experience. Additionally, there is an urgent need to reduce the environmental impact of single-use masks by investigating sustainable, reusable alternatives[227].

Another area that merits further investigation is to refine the social distancing rules based on variables such as wind conditions and virus variants [88]. Future research should aim to develop more nuanced recommendations for appropriate distancing across various scenarios, balancing effectiveness and practicality. By addressing these aspects, nonengineering strategies can continue to evolve as vital components of infection prevention, contributing to more sustainable, comfortable, and adaptable solutions for public health.

2.9.12 Engineering Control Strategies

The use of engineering control strategies to improve IAQ has shown significant promise, but further research is needed to optimise these measures. For example, he use of HVAC systems during pandemics has been debated—some argue that HVAC systems can exacerbate the problem, while others recommend their use to dilute contaminants in indoor spaces [176]. This controversy highlights the need for a deeper analysis of HVAC design and operational methods, with a focus on identifying optimal configurations and usage strategies for pandemic settings.

Air cleaners (or purifiers) are one of the most frequently proposed optimisation technologies for IAQ, which heavily rely on the type of filter medium used. Among the most effective filters are HEPA, ionisers, and ultraviolet germicidal irradiation (UVGI) systems. These can either be portable or integrated into a building's ventilation system. However, portable filters are limited to cleaning the air in their immediate vicinity. For instance,Ren et al. [190] found that portable air cleaners (PACs) equipped with HEPA filters can effectively reduce aerosol build-up in rooms with poor mechanical ventilation. However, Bluyssen et al. [191] pointed out that mobile HEPA systems can generate an unacceptable background noise level. Future research should focus on the practical implementation of these filters, examining potential drawbacks such as noise and exploring ways to improve their integration into indoor spaces.

Furthermore, UV-C technology, such as RM3 UV-C units, has emerged as an effective tool for reducing infection risks [194]. However, factors such as exposure time, maintenance, and service longevity can affect its efficiency. Therefore, future research should explore innovative UV-C applications, conduct real-world assessments, and develop sustainable IAQ solutions that integrate advanced filtration technologies with minimal drawbacks.

2.9.13 Computational Fluid Dynamics

CFD models have been a vital tool in many of the reviewed studies, offering detailed simulations of airflow patterns in indoor environments. For example, Razlan et al. [199] used a CFD model to investigate airflow and temperature dispersion, revealing important insights into the dynamics of air movement within enclosed spaces. Similarly, Barbosa and de Carvalho Lobo Brum [186] applied coupled multizone CFD software to evaluate the performance of different ventilation modes, filter efficiencies, and outdoor airflow rates.

However, despite the sophistication of CFD models, many studies may have overlooked critical factors such as human movement, door openings, and real-time changes in occupancy that significantly influence airflow patterns and IAQ. To advance this issue, future research should focus on refining CFD models to incorporate these dynamic elements, ensuring a more accurate and holistic representation of IA.

By integrating these variables, future simulations will better reflect real-world conditions, thereby improving the design and implementation of effective ventilation strategies. Enhanced CFD models could ultimately lead to more efficient building designs that optimise IAQ while balancing energy consumption.

2.10 Conclusion

This systematic review has underscored the complexity and urgency of addressing respiratory infection transmission in indoor environments, particularly in light of the recent COVID-19 pandemic. In particular, this review has highlighted the critical need to investigate viral transmission dynamics in enclosed spaces and the role of IAQ in mitigating infection risks. As respiratory diseases continue to pose significant public health threats, understanding the factors that influence viral spread within indoor environments is essential to develop effective prevention strategies.

The research that was reviewed demonstrates that a multifaceted approach is necessary to tackle these challenges. A combination of epidemiological, microbiological, and computational methods, including CFD simulations, has been employed to better understand how infections spread in enclosed spaces. The increasing integration of digital technologies such as Digital Twins and IoT devices has further enhanced the ability to monitor, manage, and predict IAQ in real-time. These advances, combined with AI techniques such as ML, offer valuable insights for improving decision-making processes related to IA management and infection control.

From an extensive review of 2,722 articles, 178 were identified as key contributors to our understanding of SARS-CoV-2 transmission, IAQ assessment, and control strategies in pandemic contexts. This body of work has not only provided critical insights into the interplay between ventilation, filtration, and infection control strategies but has also revealed notable gaps in current research. Specifically, a limited number of studies have addressed the impact of energy consumption in the context of IAQ control, which emphasises the need for a more integrated approach that balances infection prevention with sustainability.

Further gaps include the lack of a comprehensive analysis of specific indoor environments, insufficient consideration of the indoor and outdoor parameters, and inadequate assessment of occupancy patterns in IAQ studies. These limitations highlight the need for future research to adopt more holistic methodologies, incorporating energy-efficient practices alongside IAQ improvements.

A key takeaway from this review is the importance of integrating digital twins and ML techniques in future IAQ research. These technologies have the potential to significantly enhance the management of IA by providing real-time data on transmission patterns and enabling more informed decision-making, while also considering energy consumption and sustainability.

In conclusion, future research should address these identified gaps by leveraging advanced technologies and adopting a more comprehensive approach to IAQ management. By doing so, we can develop more sustainable and resilient indoor environments that prioritise human health while minimising energy consumption, thereby effectively mitigating the ongoing and future risks posed by respiratory viruses.

Chapter 3

Research Design and Methodology

3.1 Introduction

This chapter outlines the research methodology that will be used to explore IAQ, TC, and virus dispersion in office environments. It provides a clear roadmap for this study, ensuring rigour, transparency, and replicability. This methodology integrates experimental data collection with advanced computational modelling to comprehensively analyse ventilation strategies and their effectiveness in improving IAQ, maintaining TC, and minimising airborne virus transmission risks.

This chapter specifically addresses the following research questions:

- **Research Question 2:** Can CO2 levels serve as reliable indicators to assess IAQ and signal the potential risk of airborne infections in office environments?
- **Research Question 3:** What ventilation strategies can be implemented to minimise the risk of airborne infections in office environments?
- **Research Question 4:** How can ventilation systems be configured to maintain good IAQ, ensure TC, and reduce virus dispersion in office environments?

Although RQ1 was primarily addressed through a detailed literature review in chapter 2, this chapter also supports RQ1 by outlining the simulation methods used to model virus transmission dynamics. The CFD simulations conducted using ANSYS Fluent replicate the dispersion behaviour of airborne virus particles under different ventilation scenarios, thereby providing quantitative insights into the airflow conditions and environmental factors that influence viral transmission indoors.

As illustrated in Figure 3.1, this research begins with building information modelling (BIM) to map office space (Figure 3.7) and identify sensor locations (Figures 3.13) in a teaching office at Cardiff University. Environmental sensors are deployed to measure key parameters, including CO2 concentrations, temperature, RH, and PM (PM2.5 and PM10), over a two-month period. These measurements are analysed to determine whether CO2 can serve as a reliable indicator of infection risk, addressing one of the key objectives of this study.

For the simulation phase, ANSYS Fluent is employed to model airflow patterns, TC, and virus dispersion under three ventilation scenarios: AC system, natural ventilation through opening windows, and mixed-mode ventilation, combining AC system and natural ventilation.

These simulations provide detailed insights into how airflow affects virus dispersion and TC in office space. By comparing the results across different ventilation strategies, this study identifies the most effective methods to maintain a healthy and comfortable indoor environment, while minimising the risks of infection.

The results of these analyses will be synthesised to provide practical recommendations for improving ventilation systems. The ultimate goal is to inform the design of healthier office environments that optimise IAQ, enhance TC, and reduce risks of virus transmission.

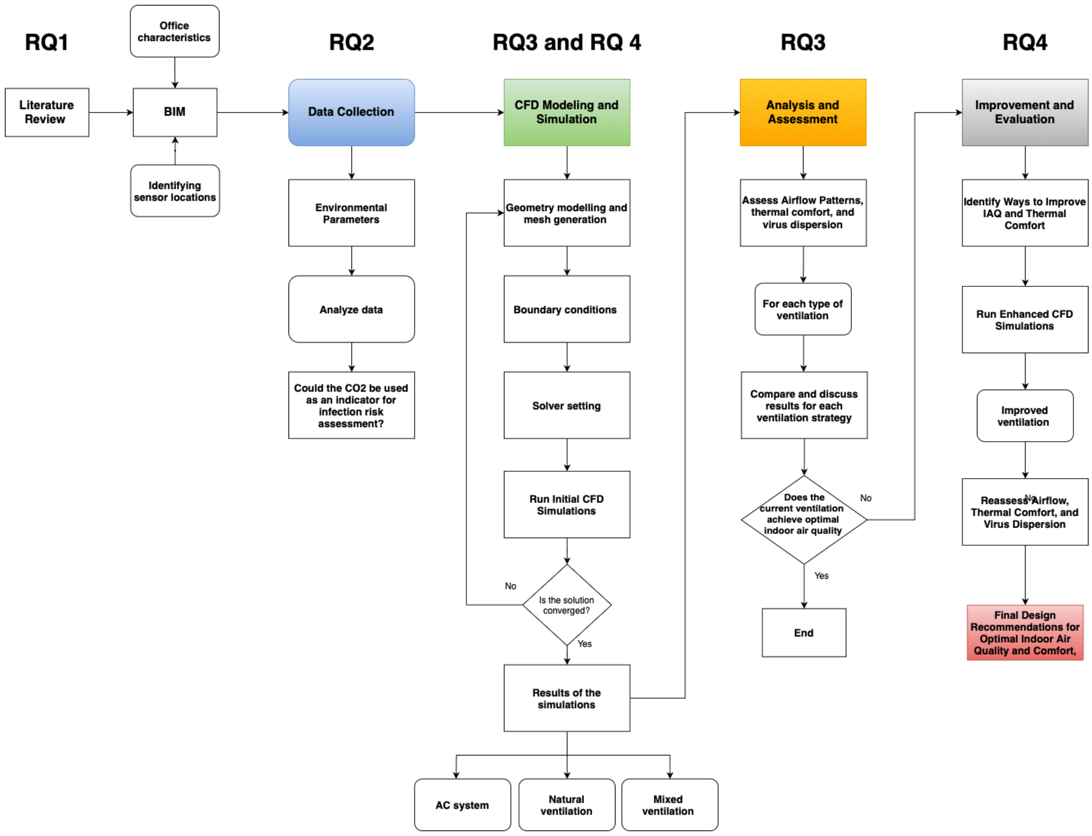


Figure 3.1: An overview of the research methodology

3.2 Demonstration Site and Building Information

The demonstration site for this research is a teaching office located within the Queen's Building at Cardiff University, UK. Located in the northeast of Cardiff city, as shown in Figure 3.2. The Queen's Building illustrated in Figure 3.3 serves as a prominent hub for academic and research activities. This multipurpose facility houses several academic departments, including the School of Engineering and the School of Physics, and supports a wide range of activities, such as lectures, research, and administrative functions. Its strategic location and diverse utilisation make it an ideal setting to investigate ventilation strategies and IAQ dynamics in office environments.

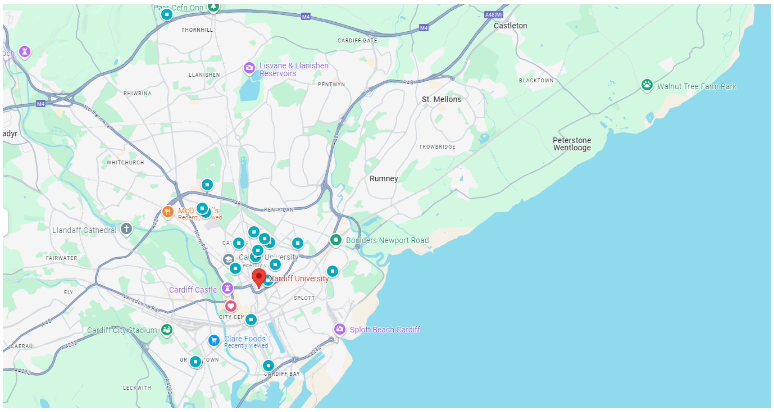


Figure 3.2: Location of the Queen's Building

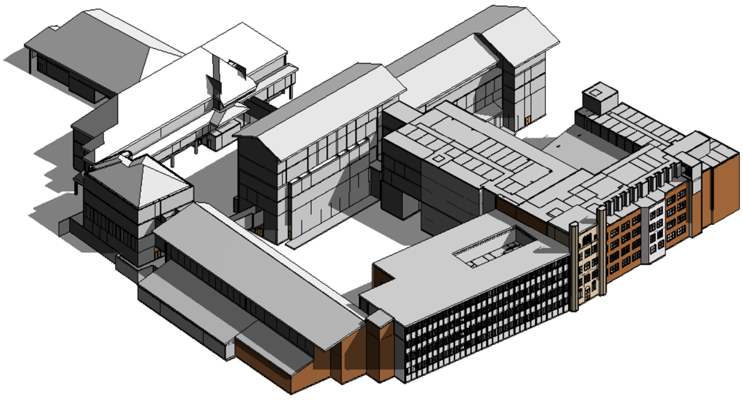


Figure 3.3: Queen's Building

3.2.1 Teaching Office Information

The specific teaching office selected for this research is located on the first floor, within the south wing of the Queen's Building, as illustrated in Figures 3.4 and 3.5. Its urban location within Cardiff University ensures that external environmental factors, such as outdoor air pollution and seasonal weather variations, reflect typical conditions in urban office settings.

The teaching office occupies a total floor area of 270 square meters, with dimensions of 18 meters in width, 15 meters in length, and 4 meters in height, as shown in the 3D Ansys Design Model in Figures 3.6 and Figures 3.7. This space was designed to accommodate up to 13 occupants and it functions as a workspace for staff and a consultation area for students, as shown in Figures 3.8. Regular interaction between the occupants creates dynamic fluctuations in occupancy, providing a practical setting for studying IAQ, TC, and ventilation performance.

The office is divided into three distinct zones to accommodate different activities:

- Zone 1: This is the largest zone, designed for nine occupants.
- Zone 2: This is a medium-sized zone, accommodating three occupants.
- Zone 3: This is a smaller zone, designated for one occupant.

The office is equipped with 18 south facing windows, as illustrated in Figure 3.9, which contribute to natural day lighting and play a significant role in ventilation dynamics, particularly in natural and mixed ventilation scenarios.

Access to the teaching office is provided through two doors, as illustrated in Figure 3.10:

- North-facing door: This door remains open during operational hours, allowing passive airflow. It opens into a hallway that connects to the forum, which is used by the students to study or eat.
- West-facing door: This door is typically closed and is only used by employees who enter or leave the office.

Ventilation is primarily managed through an AC system comprising six ceiling-mounted fan coil units (FCUs), as shown in Figure 3.11. These FCUs play a critical role in regulating indoor temperature and airflow. However, they do not introduce fresh air from the outside, relying instead on recirculating existing indoor air. This limitation highlights the importance of exploring additional ventilation strategies, such as natural or mixed ventilation, to improve IAQ and reduce the risks of airborne infection.

The teaching office was chosen as the demonstration site due to the following factors:

- Representative of a common workspace: The teaching office represents a typical workspace within an academic setting, making the findings of this study applicable to similar office environments in both academic and professional contexts.
- Mixed ventilation system: This site features a combination of natural ventilation (operable windows) and AC ventilation (FCUs), making it ideal choice to evaluate different ventilation strategies. This hybrid system enables comparisons to be made between scenarios to assess their impact on IAQ, TC, and virus dispersion.
- Variability in environmental conditions: Variability in occupancy levels and indoor environmental conditions, such as temperature, humidity, and CO2 concentrations, offers a dynamic setting for analysing how these factors influence IAQ and virus dispersion.
- Ease of access for data collection: The accessibility of the teaching office facilitates continuous and systematic data collection without logistical constraints. This ensures the acquisition of comprehensive and high-quality environmental data throughout the study period.
- Predictable working schedule: This office operates on consistent working hours (9 AM to 5 PM), allowing for structured monitoring of occupancy patterns and environmental conditions. These predictable patterns provide a controlled framework for analysing relationships between human activities and IAQ parameters.

This teaching office offers a unique opportunity to investigate the interplay between ventilation strategies, TC, and virus dispersion. The combination of natural and AC ventilation systems provides a robust platform to compare different approaches to optimise IAQ and minimising infection risk. Regular interaction between staff and students further enriches the study by introducing real-world occupancy fluctuations, which is closely aligned with this study's objective of identifying effective ventilation strategies for indoor environments.

Figure 3.4: Location of the teaching office

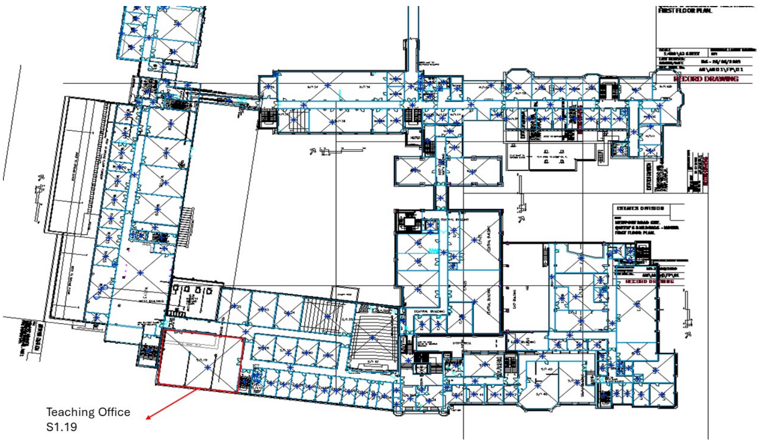


Figure 3.5: The teaching office S1.19

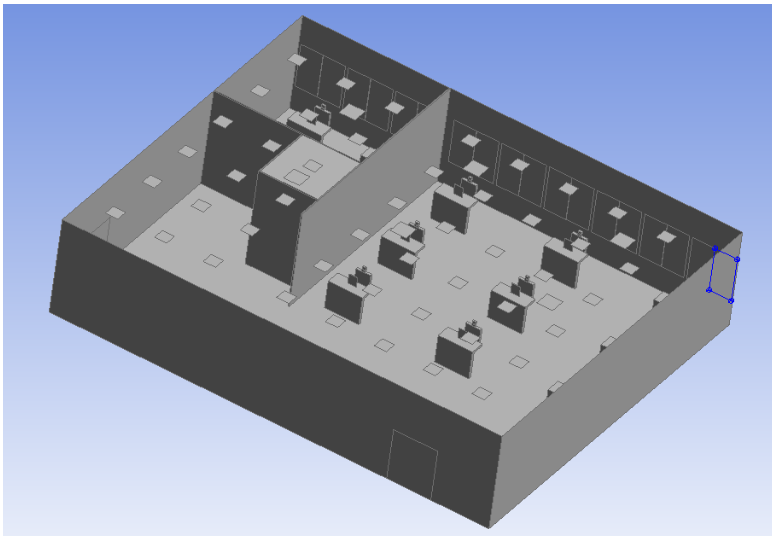


Figure 3.6: The teaching office S1.19 using Ansys

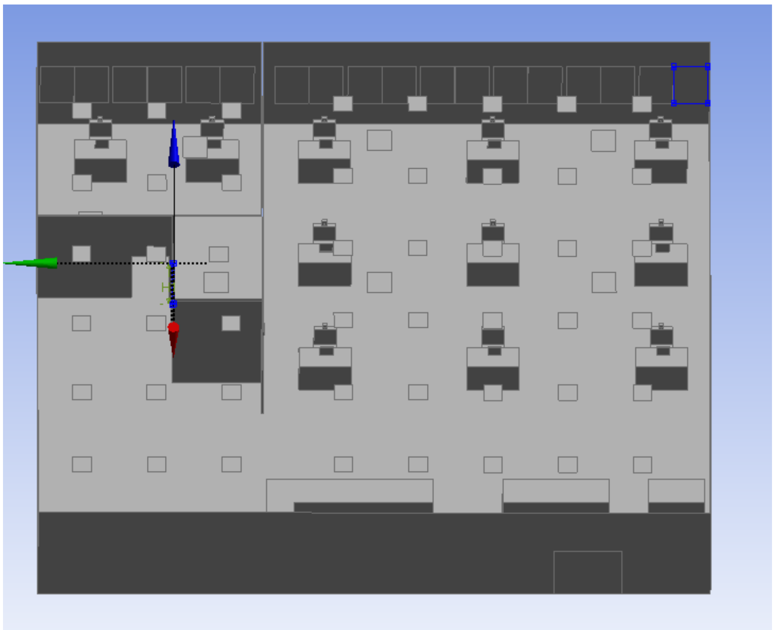


Figure 3.7: Teaching office area

Figure 3.8: Teaching office area: 18 south-facing windows

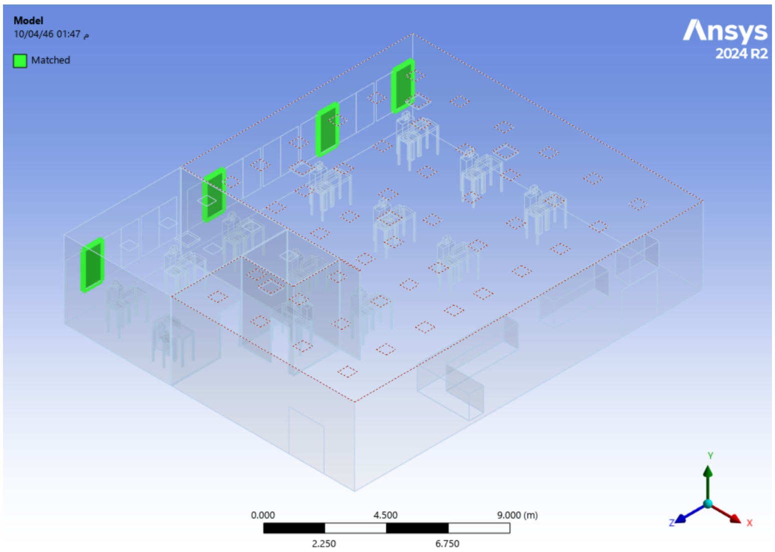


Figure 3.9: The 18 south-facing windows

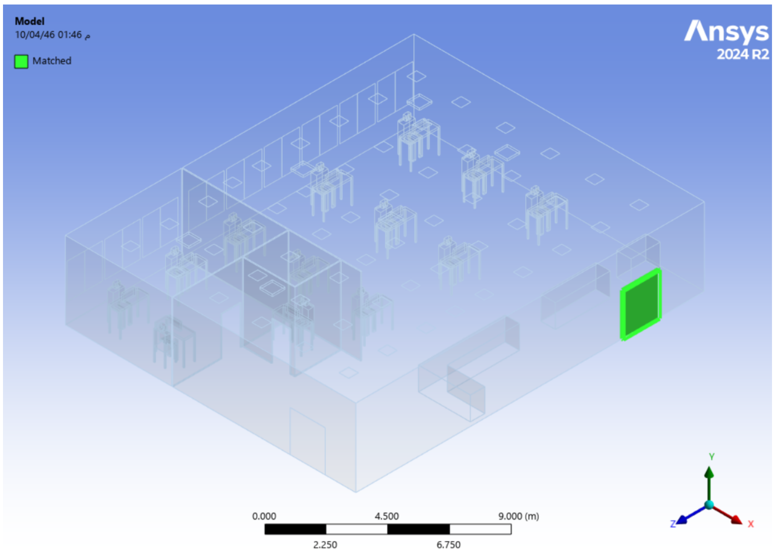


Figure 3.10: The doors in the teaching office

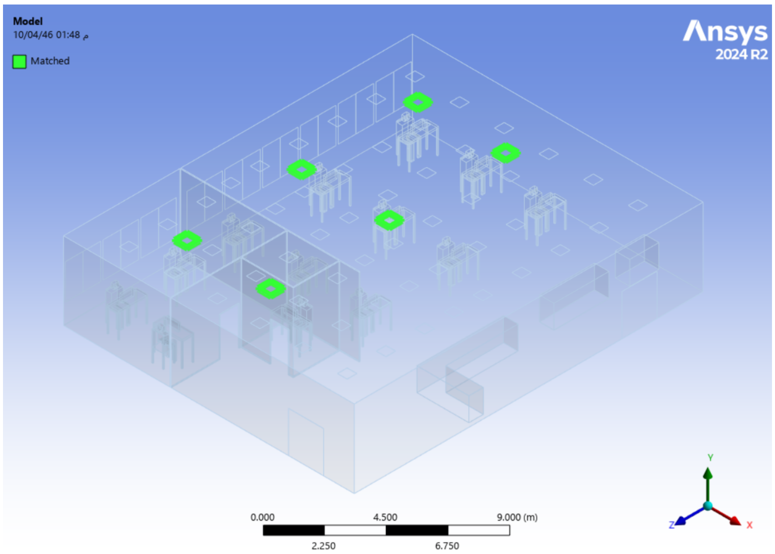


Figure 3.11: Design of the AC system

3.3 Monitoring and Instrumentation

This section describes the IoT-based environmental monitoring system that will be used in this study to capture both indoor and outdoor environmental parameters. By integrating data from indoor sensors and an on-site weather station, the system provides a comprehensive understanding of the factors that influence IAQ, TC, and virus dispersion.

The monitoring system consists of three primary components:

- End Devices (Remote Units): These devices are equipped with integrated sensors to measure specific parameters. For indoor monitoring, sensors measure CO2 levels, temperature, humidity, and PM (PM2.5 and PM10). For outdoor monitoring, weather data, including temperature, humidity, and pressure, is collected via an on-site weather station.
- Gateway: The gateway receives data wirelessly from the end devices using the LoRaWAN protocol and transmits it to the server.
- Server/Database: The server processes and stores the collected data, enabling detailed analysis and interpretation.

Figure 3.12 illustrates the schematic diagram of the indoor and outdoor environment monitoring system.

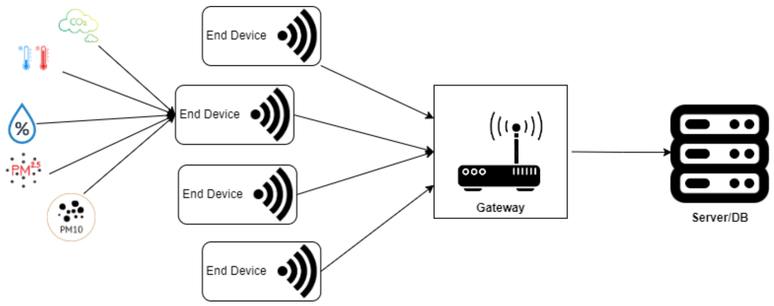


Figure 3.12: Schematic diagram of the indoor environment monitoring system

The data collected by these sensors are transmitted to a nearby gateway, which in turn forwards the data to a network server. The server processes and stores these data for subsequent analysis. Given the focus on indoor conditions, the sensing devices used in this research are categorised mainly into indoor environment sensors. The role of each sensor is to accurately monitor variables such as temperature, humidity, CO2 levels, and PM concentrations.

A detailed description of each sensing device is provided, including a classification based on functionality. Table 3.1 offers a concise summary of the sensors, describing their category, model, and the associated parameters they measure. This systematic approach ensures a comprehensive understanding and analysis of indoor climate, facilitating targeted interventions to improve air quality and energy efficiency within the office environment.

Parameter(s)	Sensor	Measurement range	Accuracy
CO2	Sensirion (SCD41)	400 to 5000 ppm	± 40 ppm
RH	Bosch (BME680)	0 to 100%r.H	± 3%r.H
Temperature	Bosch (BME680)	-40 to 85 C	± 0.5 C
Pressure	Bosch (BME680)	300 to 1100 hPa	± 0.6 hPa
PM	Plantower (PMS5003)	0 to 500 μg/m^3	± 10 μg/m^3
Weather data	Davis(Vantage Pro2)	Follow the link [1]	

Table 3.1: An overview of the technical specifications of the utilised sensing devices..

Indoor environment sensor In this investigation, a variety of sensors were used to measure various indoor parameters, such as temperature, humidity, CO2 levels and PM. These sensors were integrated into a single box, which was referred to as the 'end device', as illustrated in Figure 3.12. The descriptions of these sensors are as follows:

- The CO2 sensor (Sensirion SCD41): This sensor utilises nondispersive photoacoustic infrared technology to measure CO2 concentrations in the air. The principle behind this technology is based on CO2 molecules that absorb

[1] https://www.davisinstruments.com/pages/vantage-pro2

infrared energy, leading to molecular vibrations within the measurement chamber. These vibrations generate acoustic waves, which a microphone then detects to determine the CO2 levels.

- The temperature sensor (Bosch BME680): The indoor temperature is measured on the basis of voltage variations in a silica diode. The fundamental operating principle of this sensor is that the voltage changes of the diode correspond to changes in the ambient air temperature.

- Humidity sensor (Bosch BME680): This sensor operates on the principle of capacitive sensing to measure the presence of water vapour in the air. The humidity level is measured by tracking changes in the electrical capacitance of a polymer-based capacitor, which varies with the amount of moisture present.

- Pressure sensor (Bosch BME680): This sensor gauges indoor atmospheric pressure by observing the deformation of an extremely sensitive thin membrane that responds to variations in atmospheric pressure.

- The PM sensor (Plantower PMS5003): This sensor measures the concentration of two types of pollutants, PM10 and PM2.5, in the air. It detects particles by projecting a light source, usually a laser beam, through an air sample. The light scattering caused by these particles is then analysed to determine the mass concentration of the PM in microgrammes per cubic metre (mug/m^3).

Weather data (Davis Vantage Pro2)): An industrial grade weather station was put on the roof of the west building. The weather station uses a variety of sensors to collect real-time data on over 20 variables, such as temperature, humidity, pressure, precipitation, wind direction and speed, sun radiation, etc.

3.3.1 Indoor Environmental Monitoring

Primary data were collected using advanced remote sensing units strategically placed throughout the research site, as shown in Figure 3.13. These sensors continuously measured key parameters that are critical for evaluating IAQ, TC, and ventilation effectiveness. The monitored parameters included:

- Temperature: This is recorded to evaluate TC and to analyse the effect of temperature variations on airflow dynamics and occupant comfort.
- Humidity: This is monitored to determine indoor moisture levels, which affect both comfort and the potential for virus transmission.
- CO2 Levels: These are used as a proxy for air quality and ventilation performance, elevated levels indicate insufficient ventilation.
- PM: The concentrations of PM2.5 and PM10 were measured to assess the presence of airborne particles that could impact the health of the occupants.

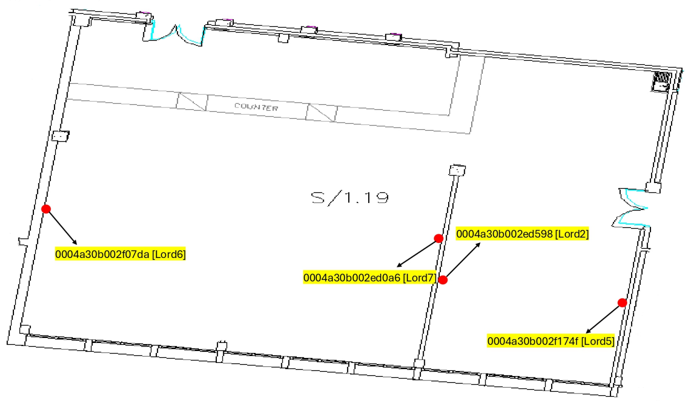


Figure 3.13: Location of the sensors in the teaching office

3.3.2 Outdoor Environmental Monitoring

To provide a context for indoor measurements, outdoor environmental conditions were also monitored during the same two-month period. The outdoor parameters included:

- Outdoor temperature: This was captured to analyse how fluctuations in external temperature influence indoor thermal conditions and ventilation needs.
- Wind speed and direction: These were measured to assess their impact on natural ventilation and the potential infiltration of outdoor air into the indoor environment.

3.4 CFD Modelling and Simulation

This section presents the CFD methodology that will be used to simulate airflow patterns, TC, and dispersion of viral particles in an office setting teaching. This study employs ANSYS Fluent®, a widely used CFD solver, to provide detailed information on fluid flow behaviour, ventilation effectiveness, temperature and humidity gradients, and occupant-generated aerosols. Understanding how airborne pathogens circulate under different ventilation strategies is essential to mitigate transmission risks, while ensuring a comfortable and healthy indoor environment.

ANSYS Fluent was selected for this study due to its advanced turbulence modelling capabilities, robust multiphysics integration, and well-validated accuracy in IAQ simulations. Compared to other CFD programmes, ANSYS Fluent offers superior flexibility in handling complex boundary conditions, particularly when modelling ventilation-driven contaminant transport, thermal effects, and multiphase flows. It has been shown to provide slightly better performance in certain aspects than STAR-CCM+, as demonstrated in a study by [228], particularly in terms of numerical stability and solver efficiency for indoor airflow simulations.

Furthermore, comparative research has shown that ANSYS Fluent delivers more consistent solution accuracy at lower computational costs, while offering more versatile visualisation capabilities than SolidWorks or SimScale [229]. The software's user-defined functions (UDFs) further enhance its capabilities, allowing for custom modelling of airborne virus transmission risks and pollutant transport dynamics. These features make ANSYS Fluent a highly reliable tool for evaluating IAQ, infection risk, and TC performance in different ventilation strategies.

Using ANSYS Fluent's advanced computational capabilities, this study ensures a comprehensive assessment of ventilation performance in an occupied office environment, which will contribute to the development of optimised IAQ control measures.

3.4.1 CFD Objectives

The CFD-based investigation will evaluate three ventilation strategies (i.e., AC system, natural, and mixed-mode ventilation) in a teaching office at Cardiff University. Each strategy is analysed for its ability to reduce infection risks, improve IAQ, and maintain the TC of the occupants. The specific aims are as follows:

- Identify strengths and limitations of the AC system, natural, and mixed-mode ventilation systems to control airborne infection risks and maintain occupant comfort.
- Investigate how different ventilation scenarios affect airflow distribution, droplet trajectories, and thermal conditions.
- Recommend design optimisations and operational guidelines to improve IAQ, TC, and occupant safety.

3.4.2 CFD Methodology

3.4.3 Materials and Methods

IAQ is determined by a combination of factors, including airflow rate, temperature, humidity, and CO2 concentration. These parameters significantly influence the health, comfort, and safety of the occupants in enclosed spaces, particularly in office environments where inadequate ventilation can increase the risk airborne virus transmission [230]. The COVID-19 pandemic brought global attention to the consequences of poor ventilation, with documented cases of virus spread among office workers, which highlighted the critical role of effective air circulation [231].

To address the multifaceted challenges associated with IAQ and airborne infection risks, in this study a numerical approach is adopted that will use CFD. CFD offers the ability to simulate airflow patterns, TC, and virus dispersion in varying ventilation strategies, providing a detailed understanding of how these factors interact in an office setting. The simulations, which will be performed using Ansys R18.1, focus on evaluating key performance indicators such as airflow distribution, TC, and the trajectory of aerosolised particles.

3.4.3.1 Key Steps in the CFD Workflow

CFD simulations in Ansys Fluent follow a structured workflow consisting of three main stages: preprocessing, solver configuration, and postprocessing. Figure 3.14 visually outlines these steps, ensuring a systematic approach to accurately modelling airflow dynamics, TC, and pollutant dispersion in indoor environments. The following key steps are taken:

- Geometry modelling and mesh creation: Developed in Ansys DesignModeler and Ansys Meshing, followed by a grid independence study to ensure accuracy.

- Definition of boundary conditions, material properties, and solver parameters.
- UDF compilation: Incorporating custom functions for PMV/PPD calculations.
- Solver settings and run cases: Selection of turbulence model
- Generating contour plots for velocity, temperature, RH, TC (PMV and PPD), and particle dispersion.

3.4.4 Model Development

3.4.4.1 Assumptions of this Research

The development of the computational model for this study is based on a set of well-defined hypotheses and assumptions to simplify the analysis and align the simulations with the specific operational conditions of the teaching office. These assumptions ensure a focused investigation of airflow patterns, TC, and virus dispersion in various ventilation scenarios.

- Four different locations for infected individuals: This study hypothesises that the dispersion of airborne pathogens varies based on the spatial position of an infected individual. Therefore, four distinct locations within the office have been strategically selected to simulate potential infection scenarios. These positions represent typical occupant activities and ensure that airflow interactions are comprehensively analysed.
- Natural ventilation scenarios assume 30% of open windows: For natural ventilation cases, some windows are assumed to be open, providing maximum

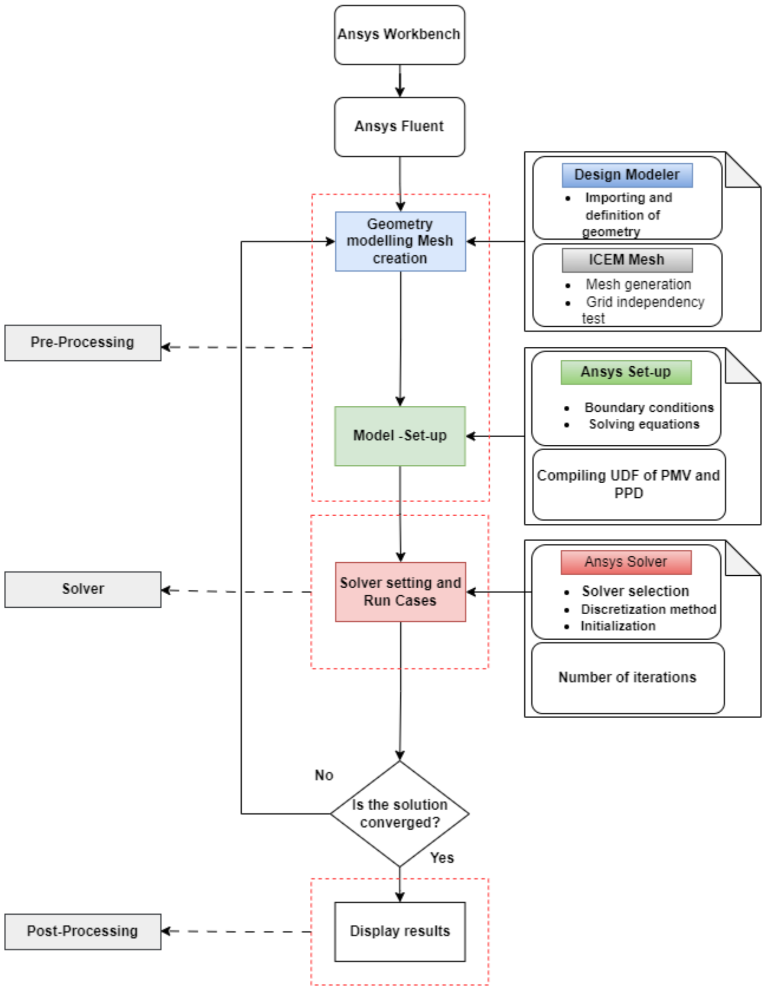


Figure 3.14: Steps of Ansys

potential for outdoor air exchange. Scenarios involving partially closed or fully closed windows are not simulated, simplifying the assessment of natural ventilation's effectiveness.

- Steady-state indoor conditions: The model assumes steady-state conditions in AC system and is transient with particles.
- Uniform indoor temperature distribution: The temperature is assumed to be evenly distributed throughout the office space.
- Uniform occupant activity levels: All occupants are presumed to participate

in similar activities, contributing equivalent amounts of CO2 and aerosols to the indoor environment. This standardisation facilitates a clearer correlation between occupancy and IAQ metrics.

- Room air is perfectly mixed in mixing ventilation scenarios: For mixing ventilation scenarios, it is assumed that the air within the room is uniformly mixed, ensuring consistent concentrations of contaminants throughout the space.
- Exclusion of other indoor pollutants: This study focusses exclusively on temperature and RH. The analysis does not consider other pollutants, such as CO2, PM (PM2.5 and PM10), virus-laden aerosols, VOCs, or O3.
- Fixed occupancy patterns: This study assumes that the occupancy levels remain constant during working hours. Dynamic changes, such as the presence or absence of occupants in the space, are not accounted for in the model.

3.4.4.2 Governing Equation

In ANSYS Fluent, the foundational principles governing fluid motion are based on conservation of momentum, mass, and energy. These principles are mathematically represented by the Navier—Stokes equations (momentum conservation), the continuity equation (mass conservation), and the energy equation (energy conservation). These equations collectively form the core framework for simulating airflow, temperature distribution, and aerosol dispersion in indoor environments. The equations shown below are integral to CFD simulations, allowing accurate modelling of complex fluid behaviours under varying conditions [232]. **Momentum Conservation** The conservation of momentum governs the transport of momentum in the fluid and is represented by the Navier–Stokes equations:

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u \vec{V}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + \rho f_x \tag{3.1}$$

$$, \frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v \vec{V}) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + \rho f_y \tag{3.2}$$

$$, \frac{\partial(\rho w)}{\partial t} + \nabla \cdot (\rho w \vec{V}) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z, \tag{3.3}$$

where p is the pressure of the fluid and ρ is the density of the fluid (mass per unit volume). Meanwhile, u,v, w represent the velocity components in the x, y, and z directions, respectively. τ_{ij} are components of the stress tensor, representing viscous forces (shear stresses and normal stresses), and τ_{xx},τ_{xy} and τ_{xz} are stresses in the x direction due to velocity changes in the x, y, and z directions. ρf_x, ρf_y, and ρf_z represent body forces (e.g., gravity or other external forces) acting in the directions x, y, and z, respectively.

Mass conservation The continuity equation ensures the conservation of mass within the system:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\vec{V}\right) = 0 \tag{3.4}$$

Energy conservation The conservation of energy governs the transport of thermal energy within the fluid:

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\vec{v}(\rho E + p)) = \nabla \cdot \left(\sum_j h_j \vec{J}_j\right) + S_h, \tag{3.5}$$

where E is the total energy per unit mass of the fluid, typically the sum of internal energy (from molecular motion), kinetic energy, and potential energy.

These governing equations, in combination with boundary conditions and turbulence models, enable the accurate simulation of airflow dynamics and the dispersion of aerosols within the indoor teaching office.

3.4.5 Boundary Condition

The present study uses a detailed CFD simulation framework to evaluate ventilation strategies in a teaching office environment. This section outlines the general boundary conditions and modelling assumptions that will be applied to all simulation cases, while specific ventilation configurations are described in subsequent chapters. The simulation domain and boundary settings have been selected to ensure robust and physically representative predictions of air quality, TC, and infection risk.

Air will be treated as an incompressible fluid, a valid assumption given the low-speed airflow conditions that are typically encountered in indoor environments [233]. Turbulence will be modelled using the k-ϵ RNG model, which was selected for its improved precision in predicting recirculating flows and low Reynolds number effects compared to the standard k-ϵ model [234].

The transit-state airflow field and turbulence parameters were first solved using the COUPLED algorithm for pressure-velocity coupling. Second-order upwind schemes were applied to all governing equations to improve accuracy and minimise numerical diffusion.

All solid boundaries, including walls, floors, and occupant surfaces, will be treated as nonslip walls, ensuring the correct resolution of boundary layer effects and airflow near surfaces. The walls will be modelled as adiabatic, following standard assumptions in indoor airflow simulations, where heat transfer through the walls is considered secondary to convective effects [235].

To account for internal heat sources, the ceiling will be assigned a constant heat flux of 40 W / m^2, representing the gain in lighting heat, which typically accounts for 25% of total internal heat generation in office environments [233]. Furthermore, occupant heat generation will be modelled as a fixed internal heat source of 120 W per person, based on metabolic rates of 1.5 Met and clothing insulation levels of 0.5 clo (summer) and 1 clo (winter) [219]. These assumptions ensure a realistic representation of heat loads during work hours.

To model airflow exiting the domain, a pressure outlet boundary condition will be applied to all exhaust regions, with the outlet pressure set to 0 Pa (relative to atmospheric pressure). This condition allows the solver to determine pressure-driven airflow distributions based on AC and natural ventilation influences.

To verify the suitability of this boundary condition, simulated pressure distributions and airflow rates are compared with experimental and numerical studies of similar indoor ventilation environments [236].

A DPM will be used to investigate the dispersion of respiratory aerosols, tracking individual particle trajectories in a transient manner. The simulation framework follows a Transient DPM tracking: Once a fully developed airflow field has been obtained, particle dispersion is simulated over a 400-second period.

Respiratory aerosol particles are injected into the domain with a size distribution ranging from 7×10^{-6} m to 1×10^{-4} m, with a mean diameter of 7.44×10^{-5} m, consistent with experimental data on human emissions. The following respiratory events are simulated on the basis of established respiratory airflow models [237, 238]:

- Coughing: The particles are expelled at 11.8 m/s for 1.3 to 2.3 s.
- Sneezing: The particles are expelled at 70 m/s for 0.1 to 1.1 s.

The expelled aerosols are assigned a temperature of 35°C to approximate the properties of the exhaled air. The DPM is implemented in a one-way coupling mode, assuming a dilute particle concentration that does not influence the airflow field, which is a widely accepted approach for IAQ simulations [239].

The CFD simulations are performed using a segregated solver, with convergence criteria based on residual reduction and stabilisation of key flow variables. The following convergence thresholds are applied:

- Momentum, energy, and turbulence: Convergence is defined as residuals that drop below 10^{-5} for the momentum and turbulence equations.
- Continuity equation: A stricter criterion of 10^{-6} is enforced to ensure mass conservation.

To ensure numerical accuracy, a grid independence study will be conducted, refining the mesh resolution until further refinement produces negligible changes in airflow parameters. Similarly, a time-step sensitivity study confirms that the transient DPM tracking accurately captured particle dispersion without introducing numerical artefacts.

3.4.6 Solver Setting

This study employs a hybrid Eulerian-Lagrangian approach, where the continuous air phase is solved using Eulerian methods, while the movement of virus-laden aerosols is modelled using the Lagrangian DPM. This approach enables accurate simulation of airborne particle trajectories, dispersion patterns, and potential inhalation risks under varying airflow conditions.

The simulation process consists of two major computational stages. First, a steady-state flow solution is established by solving the Reynolds-averaged Navier–Stokes (RANS) equations using the renormalisation group (RNG) k-ϵ turbulence model. This turbulence model was selected because of its ability to accurately resolve indoor airflow characteristics and ventilation-induced turbulence. The solution is deemed convergent when the residuals for the continuity, momentum, turbulence, and energy equations drop below 10^{-5}, typically requiring around 2000 iterations. After the steady-state airflow field is fully developed, the second stage of the simulation, transitory particle tracking, is initiated. In this phase, the unsteady DPM is employed to track the motion of virus-laden aerosols expelled during coughing events. Particle injections are introduced after steady-state airflow is achieved to ensure a stable and reliable analysis of airborne particle dispersion and transport.

To differentiate the computational time scales, two key concepts are introduced: flow time, which refers to the steady-state distribution of velocity, temperature, and airflow; and particle time, which represents the transient dispersion of aerosols over time. This distinction ensures that airflow dynamics and aerosol transport are analysed separately, preventing numerical instability and ensuring accurate predictions of airborne virus transmission patterns.

The governing equations for mass, momentum, and energy conservation are employed to describe airflow behaviour, expressed as:

$$\nabla \cdot (\rho \mathbf{u} \phi) = \nabla \cdot (\Gamma_\phi \nabla \phi) + S\phi, \tag{3.6}$$

where ϕ represents the solved variables, such as velocity and temperature, ρ is the density of the air, $\mathbf{u}$ is the velocity vector, Γ_ϕ represents the diffusion coefficient, and $S\phi$ accounts for source terms such as heat generation. For aerosols laden with viruses, the DPM in the Lagrangian framework is applied, where Newton's second law governs particle motion [240]:

$$\frac{d\mathbf{u}_p}{dt} = F_D(\mathbf{u} - \mathbf{u}_p) + \frac{\mathbf{g}(\rho_p - \rho)}{\rho_p} + \mathbf{F}_x, \tag{3.7}$$

where $F_D(\mathbf{u} - \mathbf{u}_p)$ represents the drag force per unit of particle mass, g accounts for gravitational settlement, and $\mathbf{F}_x$ includes additional forces such as Brownian motion. The drag coefficient, F_D is determined by:

$$F_D = \frac{18\mu}{\rho_p d_p^2} \frac{C_D Re}{24}, \tag{3.8}$$

where C_D is the drag coefficient and Re represents the relative Reynolds number, defined as:

$$Re = \frac{\rho d_p |\mathbf{u}_p - \mathbf{u}|}{\mu}. \tag{3.9}$$

This formulation enables precise predictions of particle motion and dispersion in different ventilation configurations.

To account for turbulence effects on particle dispersion, the stochastic tracking model (random-walk method) is employed. This model captures instantaneous velocity fluctuations, resulting in a realistic representation of virus-laden aerosol movement. The fluctuating velocity component is defined as follows:

$$\mathbf{u} = \overline{\mathbf{u}} + \mathbf{u}', \tag{3.10}$$

where $\overline{\mathbf{u}}$ represents the mean velocity and $\mathbf{u}'$ denotes the fluctuating turbulent component. The prediction of particle dispersion makes use of the concept of the integral time scale T, which describes the time spent in turbulent motion along the particle path ds:

$$T = \int_0^\infty \frac{u_j'(t)u_j'(t+s)}{u_j^2} ds. \tag{3.11}$$

The integral time is proportional to the particle dispersion rate because larger values indicate more turbulent motion in the flow. It can be shown that the diffusivity of the particles is given by $u_i'u_j'T$.

For small "tracer" particles that move with the fluid (zero drift velocity), the integral time becomes the fluid Lagrangian integral time T_L. This time scale can be approximated as follows:

$$T_L = C_L \frac{k}{\epsilon}, \tag{3.12}$$

where C_L is to be determined because it is not well known. By matching the diffusivity of tracer particles, $u_i' u_j' T_L$, to the scalar diffusion rate predicted by the turbulence model, ν_t/σ, one can obtain the following.

$$T_L \approx 0.15 \frac{k}{\epsilon} \tag{3.13}$$

for the k- ϵ model and its variants, and

$$T_L \approx 0.30 \frac{k}{\epsilon} \tag{3.14}$$

In this model, expelled respiratory droplets are treated as discrete particles, while the surrounding airflow field is modelled as a continuous phase. This hybrid Eulerian-Lagrangian approach enables accurate tracking of aerosol trajectories, dispersion patterns, and deposition behaviour within the indoor environment.

To properly simulate aerosol dispersion, the particle injection process is carefully defined within the DPM framework. The expelled particles exhibit a range of diameters, rather than a uniform size, requiring the use of the Rosin–Rammler logarithmic distribution method to capture the realistic variation in droplet sizes. This approach ensures that the simulation reflects the actual size distribution of virus-laden aerosols, which influence suspension time and transport distance.

The hybrid initialisation approach is adopted because it provides an optimised starting point for the distributions of temperature, turbulence, species fraction, and volume fraction. This technique uses domain-averaged values and interpolation methods to initialise the simulation efficiently, which reduces computational time while ensuring convergence.

Upon completion of the simulation, postprocessing techniques are employed to analyse virus particle tracking based on the output residence time. Animations and visualisations of aerosol dispersion are generated that illustrate the release, movement, and disappearance of virus-laden particles over time. The results reveal different dispersion characteristics for coughing and sneezing events. Specifically, aerosol transport after a coughing event occurs over a period of 1.3 to 2.3 seconds, while sneezing disperses particles within 0.1 to 1.1 seconds.

3.4.7 Thermal Comfort Simulation

This study employs CFD to evaluate TC in a teaching office environment, integrating PMV and PPD indices. These indices, defined by ASHRAE Standard 55 (2010) and ISO 7730 (2005), quantify thermal sensation and occupant dissatisfaction levels, respectively. By incorporating PMV and PPD into CFD simulations using ANSYS Fluent®, this study provides a detailed spatial analysis of thermal conditions in AC, natural, and mixed ventilation scenarios.

The TC simulation requires both environmental and physiological parameters. The environmental parameters incorporated into the CFD model include air temperature, mean radiant temperature, air velocity, and RH. These variables were extracted from steady-state CFD simulations, ensuring an accurate representation of indoor thermal conditions. The physiological parameters were established assuming a metabolic rate of 1.5 was achieved, corresponding to light office work, and 1.5 Met and clothing insulation levels of 0.5 clo (summer) and 1 clo (winter) [219]. These values ensure a realistic assessment of the thermal perception of occupants within the office environment.

The CFD model was created using ANSYS DesignModeler®, which incorporates a realistic office layout with furniture, ventilation elements, and occupants. Boundary conditions were defined for the three ventilation scenarios and heat sources from occupants, computers, and lighting systems were included to simulate realistic thermal loads. The energy equation was activated and buoyancy effects were modelled using the Boussinesq approximation, which allows for a more accurate representation of convective heat transfer within the space.

The PMV and PPD indices were computed as postprocessing output from the CFD simulations. Using UDFs, PMV was calculated based on the ISO 7730 standard equation, integrating environmental and physiological factors. The PPD index was derived from PMV using the standard equation:

$$PPD = 100 - 95 \times \exp^{\left(-0.3353, PMV^4 + 0.2179, PMV^2\right)}, \quad (3.15)$$

where PMV quantifies the thermal sensation of the occupants and PPD represents the percentage of dissatisfied individuals within the given thermal conditions. The ASHRAE PMV scale, shown in Table 7.3, categorises the thermal sensation from cold (-3.0) to hot (+3.0), providing a standardised method for assessing the comfort of the occupant.

Thermal sensation	PMV scale
Cold	-3.0
Cool	-2.0
Slightly cool	-1.0
Neutral	0.0
Slightly warm	1.0
Warm	2.0
Hot	3.0

Table 3.2: ASHRAE scale used to evaluate the thermal sensation of individuals..

3.5 Conclusion

This chapter has outlined a comprehensive and robust methodology for investigating IAQ, TC, and infection risk mitigation within a teaching office at Cardiff University. By integrating environmental monitoring, advanced CFD simulations, and rigorous validation techniques, this methodology has provided a solid foundation for analysing ventilation strategies and their impact on indoor environments.

This study begins with the selection and description of the demonstration site, highlighting its relevance and suitability in the real world to study ventilation scenarios. Indoor and outdoor environmental parameters have been systematically monitored using IoT-based sensors and an on-site weather station. Key parameters such as temperature, humidity, CO2 levels, and PM concentrations were continuously recorded, which provides critical data to validate simulations and analyse the interaction between external and internal environments.

The CFD modelling approach is central to this research and it has enabled high-resolution simulations of airflow patterns, viral particle dispersion, and TC. A realistic geometric model of the teaching office has been developed, which incorporates detailed layouts of furniture, ventilation systems, and architectural features. A carefully constructed computational mesh ensures accuracy in capturing complex airflow dynamics, with techniques such as surface refinement, volume meshing, and boundary layer meshing that address intricate interactions between airflows and obstacles.

TC is evaluated using PMV and PPD, calculated as part of the CFD simulations. These indices, based on international standards (ASHRAE and ISO), provide quantitative measures of occupant comfort under different ventilation scenarios. Environmental parameters such as air temperature, mean radiant temperature, air velocity, and RH are integrated into the simulations along with physiological factors such as metabolic rate and clothing insulation. This multifaceted approach allows this study to assess spatial variations in comfort levels and identify areas requiring improvement.

Validation processes are rigorously applied to ensure the reliability of CFD results. By comparing simulated outputs (e.g., airflow velocity, temperature distribution, and particle dispersion) with measured data and theoretical benchmarks, this study confirms the accuracy of its models. This step is essential to establish confidence in the findings and their applicability to real-world conditions.

This methodology provides actionable insights into the performance of three ventilation strategies (i.e., AC, natural, and mixed ventilation). The simulations reveal how airflow patterns influence the spread of viral particles and occupant comfort. By identifying high-risk zones and evaluating ventilation efficiency, this study delivers practical recommendations for optimising ventilation systems to create safer and healthier indoor environments.

In summary, this chapter has presented a robust framework that combines environmental monitoring, CFD modelling, and TC analysis to address some of the key challenges in IAQ and infection risk mitigation. The methods described ensure a comprehensive approach to understanding ventilation dynamics and their impact on occupant health and comfort. These methodologies form the foundation for the subsequent analysis and discussion of the results, providing valuable insights for improving IAQ and occupant well-being in office settings.

Chapter 4

Assessment and Correlation of Indoor Air Quality Parameters with Airborne Infection Risks

4.1 Introduction of CO2 and Other Parameters in an Indoor Environment

This chapter addresses **RQ2** which is: **Can CO2 levels serve as reliable indicators to assess IAQ and signal the potential risk of airborne infections in office environments?**

IAQ is a critical determinant of health, comfort, and productivity for occupants of built environments [241]. The COVID-19 pandemic has underscored the importance of understanding and mitigating airborne virus transmission risks in indoor spaces. Poor IAQ, which is characterised by elevated levels of CO2, PM (PM2.5 and PM10), and inadequate regulation of temperature and humidity, can exacerbate respiratory illnesses and create conditions favourable to suspension and airborne virus transmission [242].

High concentrations of CO2 are often indicative of insufficient ventilation, which not only affects occupant comfort but also increases the likelihood of airborne infection risks. Similarly, elevated levels of PM can serve as carriers of viral particles, further compounding the risk of respiratory diseases. Temperature and RH play a pivotal role in determining viral survival rates and transmission dynamics, with extreme conditions often favouring pathogen longevity and spread.

This chapter directly addresses Research Question 2 by evaluating the role of key IAQ parameters, including CO2 concentration, temperature, relative humidity, and particulate matter, in assessing and mitigating airborne infection risks within a teaching office environment. By systematically analysing these parameters, the study seeks to establish correlations between IAQ metrics and infection risk indicators, providing actionable insights for optimising indoor environments to improve occupant health and safety.

Furthermore, the results of this chapter will serve as a foundation for the subsequent investigation of ventilation strategies (Chapters 5, 6, and 7), where engineering solutions are explored to improve IAQ and reduce risks of airborne infection.

4.2 The Office Building and the Locations of the Sensors

The teaching office is located on the first floor of the Queen's Building at Cardiff University and serves as a shared workspace for academic staff and students. It is equipped with 13 desks that support collaborative and individual work. The office also facilitates academic consultations, making it a dynamic environment with varying levels of activity. Since the COVID-19 pandemic, the teaching office has adopted a flexible schedule to accommodate changing operational needs and public health guidelines.

To monitor IAQ and TC, four sensor stations were strategically placed within the office. These sensors measure key parameters, including temperature, RH, and CO2 levels, as shown in Figures 5.2 and 5.3. The placement of the sensors ensures comprehensive spatial coverage of the office environment, capturing variations influenced by ventilation systems, environmental conditions, and the physical layout of the space.

This monitoring setup enables a detailed evaluation of IAQ and TC in a dynamic office setting, even without precise occupancy data. This study analyses spatial and temporal variations in environmental conditions to assess the performance of existing ventilation systems and identify areas that may require improvement.

Figure 4.1: Location of two sensors in the big office

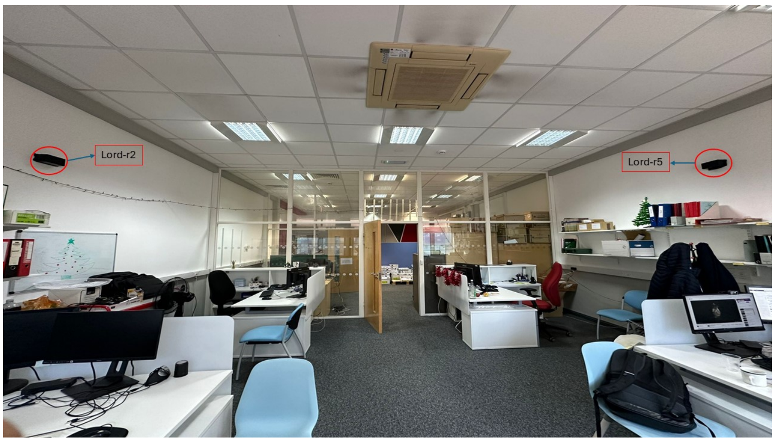


Figure 4.2: Location of two sensors in the small office

4.2.1 Data Collection

Data collection for this study was carried out systematically over a two month period, from 1 October to 30 November, during the winter season. This time frame was strategically chosen to capture the pronounced variations in indoor environmental conditions that are characteristic of the colder months, which often affect ventilation effectiveness, TC, and IAQ, thus increasing the risk of airborne viral infections. The sensors deployed in the teaching office continuously monitored temperature, RH, CO2 levels, and PM concentrations (PM2.5 and PM10), providing comprehensive data that can be used to analyse IAQ and its correlation with infection risks.

4.3 Impact of CO2 on IAQ and Comfort

CO2 concentrations play a critical role in determining IAQ and significantly influence the comfort levels of occupants in enclosed environments. As highlighted by [243], monitoring and managing CO2 levels in spaces such as classrooms can have profound effects on health, cognitive performance, and overall well-being. Elevated CO2 levels, especially when combined with suboptimal temperature and ventilation conditions, can result in discomfort, perceived poor air quality, and increased fatigue. This underscores the importance of maintaining optimal IAQ in settings where sustained attention and cognitive performance are required.

According to [244], rising CO2 concentrations, often caused by inadequate ventilation or overcrowding, not only diminish TC but also compromise the efficiency of ventilation systems. For example, in nurseries or offices with high occupancy density, increased CO2 levels lead to greater discomfort among occupants, which highlights the need for ventilation strategies that address both air quality and comfort. This also highlights the importance of ensuring adequate airflow to counteract the effects of high occupancy and poor ventilation.

Although typical indoor CO2 concentrations may not pose immediate health risks, [245] point out that CO2 acts as a reliable proxy for the adequacy of the ventilation. Elevated CO2 levels are frequently correlated with higher concentrations of bioeffluents, such as gas emissions from occupants and human activities, which can affect both comfort and perceived air quality. As such, CO2 serves as an important marker for the overall effectiveness of ventilation and its impact on IAQ. Maintaining appropriate levels of CO2 can create healthy and comfortable indoor environments that support occupant well-being and productivity.

4.3.1 CO2 as an Indicator of Ventilation and Infection Risk

CO2, a byproduct of human respiration, is widely recognised as an effective proxy for ventilation adequacy in indoor environments. Since the nineteenth century, CO2 levels have been used to evaluate IAQ. Their importance has grown in assessing airborne infection risks, particularly respiratory viruses such as COVID-19. Infected individuals exhale CO2 alongside pathogen-containing aerosols, as shown in Figure 4.3, which makes CO2 monitoring a practical and cost-effective method to estimate ventilation effectiveness and infection risk.

The primary advantage of CO2 monitoring lies in its ability to serve as a tracer gas for human respiration. CO2 concentrations can reveal ventilation performance by tracking how quickly CO2 levels decline after occupants leave a space [246]. Indoor concentrations exceeding 1,000 parts per million (ppm) often indicate inadequate ventilation, which can compromise IAQ and increase the risk of airborne virus transmission [247]. Meanwhile, maintaining CO2 levels below 700 ppm above outdoor concentrations ensures that at least 80% of the occupants perceive air quality as acceptable [246].

However, while elevated CO2 concentrations are a valuable marker of poor ventilation, they do not directly measure infection risk. The relationship between specific CO2 thresholds and airborne virus transmission risk remains uncertain and current guidelines often rely on generalised or nonspecific thresholds [248]. CO2 levels alone may not account for other IAQ factors, such as pollutants emitted by building materials or external sources, nor can they reliably indicate ventilation quality in large or sparsely occupied spaces where CO2 disperses more effectively [247].

CO2 monitoring is particularly useful in high-occupancy environments, such as offices or classrooms, where ventilation demands are higher and the potential for airborne virus transmission is significant [249]. However, its effectiveness diminishes in spaces with advanced air filtration systems, which can reduce viral particle concentrations without altering CO2 levels [250]. These limitations underscore the importance of integrating CO2 monitoring with complementary IAQ indicators, such as PM concentrations or airflow measurements, for a holistic assessment of ventilation effectiveness and infection risk.

Despite these challenges, CO2 monitoring remains a valuable and accessible tool to assess ventilation. The low cost of sensors makes them feasible for widespread use, enabling real-time evaluations of IAQ and ventilation performance. The research by [248] highlights that the volume mixing ratio of excess CO2 inhaled over time is well correlated with infection risk, which emphasises the utility of CO2 as an indirect marker for mitigating airborne virus transmission risks. Maintaining CO2 concentrations well below 1,000 ppm, in conjunction with effective ventilation and filtration strategies, can significantly reduce health risks and improve the comfort of occupants in indoor environments. However, while higher indoor CO2 levels are accepted to indicate poor ventilation, the exact concentration of CO2 associated with a specific infection risk, particularly for COVID-19, remains unclear. Although some recommendations have proposed threshold concentrations, these limits lack a robust quantitative foundation, with many guidelines suggesting a uniform CO2 threshold for infection risk [248].

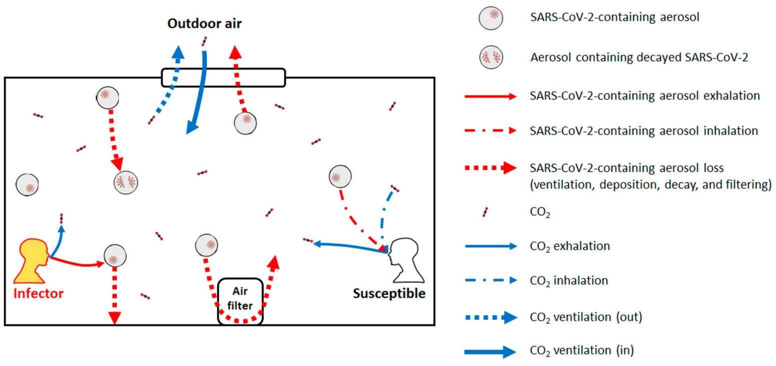


Figure 4.3: How SARS-CoV-2-containing aerosols are lost through breathing out, breathing in, and other processes; also showing how CO2 is released, breathed in, and lost through other processes in an indoor setting [248].

4.3.2 Analysis of Collected CO2 Data

Before analysing the CO2 data collected in the teaching office, it is essential to establish baseline thresholds for indoor air quality assessment. According to Cui et al. [246], maintaining indoor CO2 concentrations below 700 ppm above outdoor levels ensures that at least 80% of occupants perceive the air quality as acceptable. Conversely, CO2 concentrations exceeding 1,000 ppm are commonly recognised as indicators of inadequate ventilation, which may compromise IAQ and elevate the risk of airborne virus transmission [247].

The analysis of CO2 concentration recorded in the teaching office during October and November under the current ventilation system reveals significant daily fluctuations that are strongly correlated with the levels of office activity. Elevated CO2 concentrations were consistently observed during office hours (9:00 to 17:00). This indicates potential deficiencies in the AC system, which mainly recirculates indoor air rather than introduces fresh air.

For example, on 2 October at 13:30, CO2 levels peaked at 1089 ppm (Lord-r7), 1016 ppm (Lord-r2), 1058 ppm (Lord-r5), and 1130 ppm (Lord-r6), as can be seen in Figure 4.4. This reflects insufficient air exchange during high occupancy periods. Similarly, on 20 October at 14:06, CO2 levels reached 808 ppm (Lord-r7), 781 ppm (Lord-r2), 765 ppm (Lord-r5) and 821 ppm (Lord-r6), which further demonstrates the system's inability to maintain optimal IAQ during peak hours.

In contrast, CO2 levels were consistently lower during off-peak periods, such as weekends and nonworking hours, which is likely due to the absence of human activity. For example, on Friday 6 October at 21:39, CO2 concentrations decreased to 495 ppm (Lord-r7), 511 ppm (Lord-r2), 506 ppm (Lord-r5), and 499 ppm (Lord-r6). Similarly, on Saturday 28 October, the recorded levels were 450 ppm (Lord-r7), 414 ppm (Lord-r2), 438 ppm (Lord-r5), and 460 ppm (Lord-r6). These lower concentrations are in line with recommended IAQ thresholds, reflecting minimal occupancy and reduced CO2 emissions from human respiration.

A similar pattern persisted in November, as shown in Figure 4.5. On 6 November at 14:40, CO2 levels reached 840 ppm (Lord-r7), 825 ppm (Lord-r2), 823 ppm (Lord-r5), and 826 ppm (Lord-r6) during working hours, which further underscores the limitations of the ventilation system in managing CO2 concentrations under high occupancy conditions. In contrast, off-hour readings consistently fell below 700 ppm, which indicates that the system adequately reduces CO2 levels in the absence of significant indoor activity. For example, on Saturday 12 November the CO2 concentrations were recorded at 458 ppm (Lord-r7), 449 ppm (Lord-r2), 463 ppm (Lord-r5), and 445 ppm (Lord-r6).

The data collected throughout October and November revealed consistent patterns of CO2 accumulation during peak occupancy periods. The results indicated that CO2 concentrations frequently exceeded 1,000 ppm, particularly in the early afternoon. This aligns with occupancy schedules and suggests insufficient air exchange during those periods. However, while CO2 concentrations are strongly influenced by occupancy, the results of this study demonstrate that CO2 is not merely a passive indicator of human presence. Instead, it serves as a practical proxy for assessing ventilation effectiveness and the potential accumulation of exhaled bioaerosols in indoor environments. Elevated CO2 levels were consistently observed even during moderate occupancy periods when ventilation was insufficient—highlighting that CO2 accumulation is not solely a function of the number of occupants, but also of air exchange rates and airflow distribution. This distinction is critical, as the risk of airborne infection is closely tied to the concentration and persistence of respiratory aerosols in poorly ventilated spaces, not just the number of people present. Thus, CO2 levels offer valuable insight into the dynamic interaction between occupancy, ventilation performance, and infection risk potential—making them a useful real-time indicator for managing IAQ and occupant safety.

These findings reinforce the role of CO2 as an effective IAQ marker and support its integration into dynamic ventilation strategies. Real-time CO2 monitoring could serve as an early warning system to trigger ventilation responses and mitigate airborne infection risks proactively.

To address these challenges, the existing ventilation strategy needs to be improved. A mixed ventilation strategy, which combines natural ventilation with optimised air exchange, could provide a more robust solution. This would ensure that CO2 levels remain within safe thresholds, even during high occupancy. Furthermore, implementing real-time CO2 monitoring and adaptive ventilation controls could allow for more responsive adjustments to fluctuating indoor conditions, reducing health risks and improving overall IAQ.

4.4 Impact of Relative Humidity on Air Quality and Comfort

Indoor air humidity (IAH) significantly influences comfort, health, productivity, and infection risks, yet it has often been overlooked within the indoor air

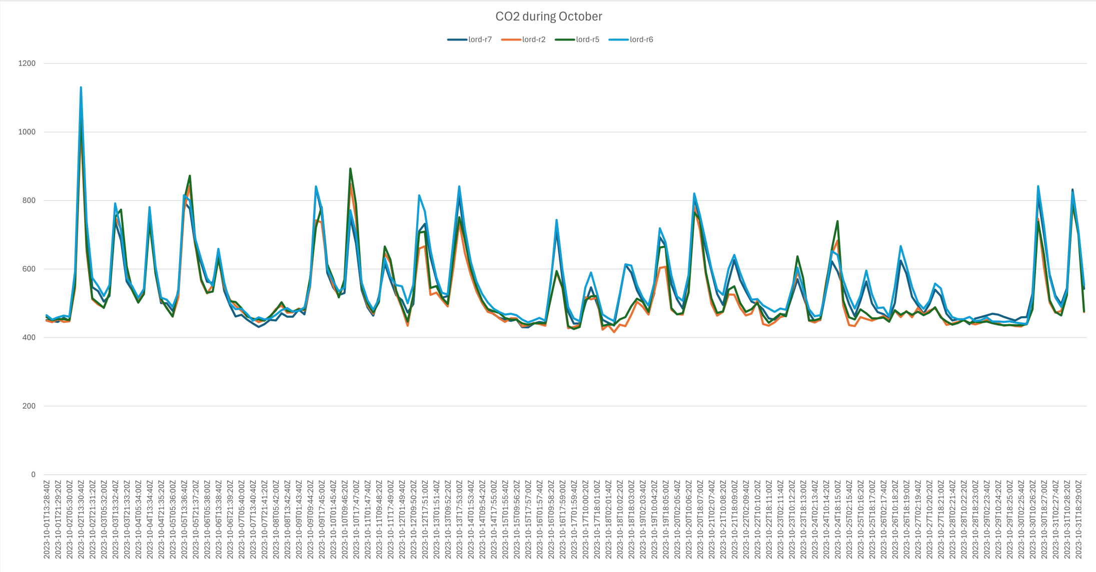


Figure 4.4: CO2 level disruption during October

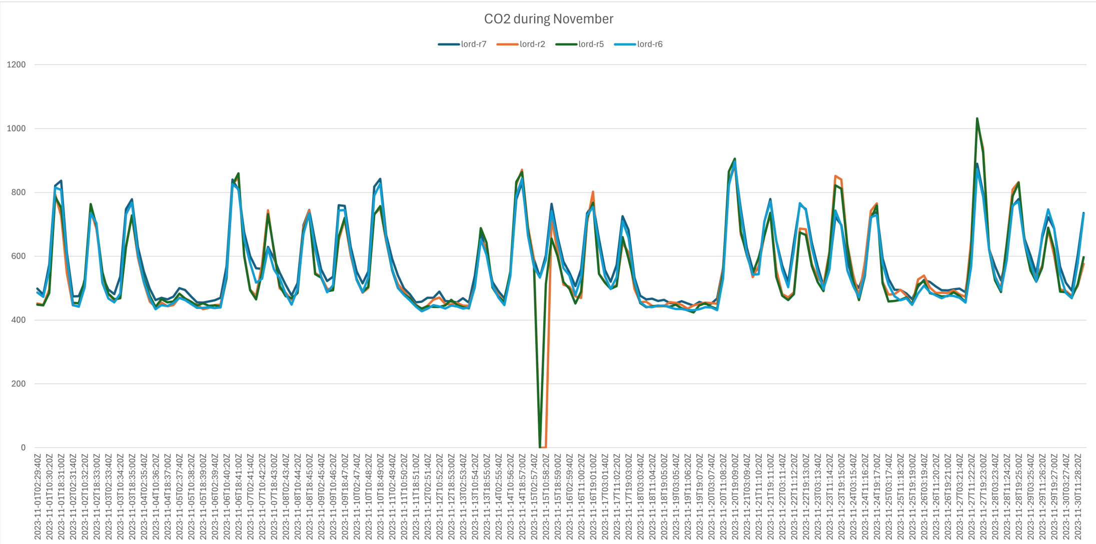


Figure 4.5: CO2 level disruption during November

research community [251]. Historically, humidification of dry indoor air was assumed to produce negligible improvements in reducing symptoms or enhancing productivity in office environments, due to inconclusive epidemiological findings. Consequently, the potential to maintain optimal RH as a non-pharmaceutical intervention to mitigate airborne virus transmission, including enveloped viruses such as COVID-19 and influenza, was underestimated [252, 253]. However, accumulating evidence over the past decade has underscored the importance of maintaining RH levels between 40% and 60%, which has been shown to reduce adverse health outcomes and improve comfort, as highlighted by [254].

Recent studies have indicated that RH levels in office environments, particularly during winter, frequently fall below the recommended threshold of 40%. For instance, Danish offices report mean RH levels of 34% during autumn, while a larger European study spanning seven countries found winter RH levels ranging from 7% to 52%, with an overall mean of 32% [255, 256]. These findings raise concerns about the prevalence of low RH levels in office environments during the colder months, where heating systems often exacerbate indoor dryness, adversely affecting both IAQ and occupant health.

Maintaining appropriate levels of RH is critical for mitigating the survival and transmission of airborne viruses. Both influenza and coronaviruses exhibit increased survival and transmission efficiency at lower levels of RH [257, 258]. Mechanistically, higher levels of RH promote virus inactivation and influence respiratory droplet size, reducing droplet evaporation and enhancing removal rates. Research shows that increasing RH can inactivate up to 28% of influenza A viruses in 10 minutes, which illustrates its protective effect on IAQ [258].

Although the relationship between RH and airborne virus transmission is multifaceted, with factors such as temperature and duration of exposure playing a critical role, maintaining intermediate levels of RH offers substantial benefits. Studies by [259] and [159] strongly advocate maintaining RH within the 40% to 60% range during the winter months. This highlights the role of RH in reducing viral transmission, improving comfort, and improving overall occupant well-being. These recommendations are grounded in robust methodologies that combine environmental measurements with symptom reporting, adding credibility to their conclusions.

By maintaining indoor RH within the optimal range, office environments can mitigate health risks associated with dry indoor air, such as increased virus survival and occupant discomfort, while improving air quality and comfort. Implementing strategies to regulate RH, particularly during the colder months, offers a practical and effective approach to creating healthier and more comfortable indoor spaces for the occupants.

4.4.1 Analysis of the Humidity Data

This subsection presents an analysis of the RH levels recorded in the teaching office during October and November, specifically during working hours (9:00 to 17:00). The data reveal consistent daily fluctuations in RH, influenced by factors such as occupant density, outdoor weather conditions, and the performance of the AC system.

In October, RH levels generally remained within the recommended comfort range of 40% to 60%. However, occasional dips below this threshold were observed, with some values falling to around 35%, as illustrated in Figure 4.6. For instance, on 16 October at 13:58, RH levels were recorded at 35% (Lord-r7), 35% (Lord-r2), 37% (Lord-r5), and 38% (Lord-r6). These fluctuations likely reflect external environmental changes or limitations in the HVAC system's ability to maintain stable humidity during periods of high occupancy.

As the monitoring period progressed into November, a noticeable decline in RH levels became evident, with values fluctuating between 47% and as low as 27% toward the end of the month as can be seen in Figure 4.7. On 30 November at 14:59, RH levels were recorded at 26% (Lord-r7), 28% (Lord-r2), 29% (Lord-r5), and 29% (Lord-r6). These measurements represent a significant deviation from the optimal RH range, particularly during colder outdoor conditions when indoor heating exacerbates air dryness.

Although RH levels in October generally adhered to the recommended range, frequent drops below 40% in November raise serious concerns. Studies by [159] and [259] emphasise the importance of maintaining a minimum RH of 40% during the winter months to mitigate viral survival and transmission risks. The observed RH values as low as 27% are especially concerning because these conditions can increase the persistence and infectivity of airborne viruses, as highlighted by [257] and [258].

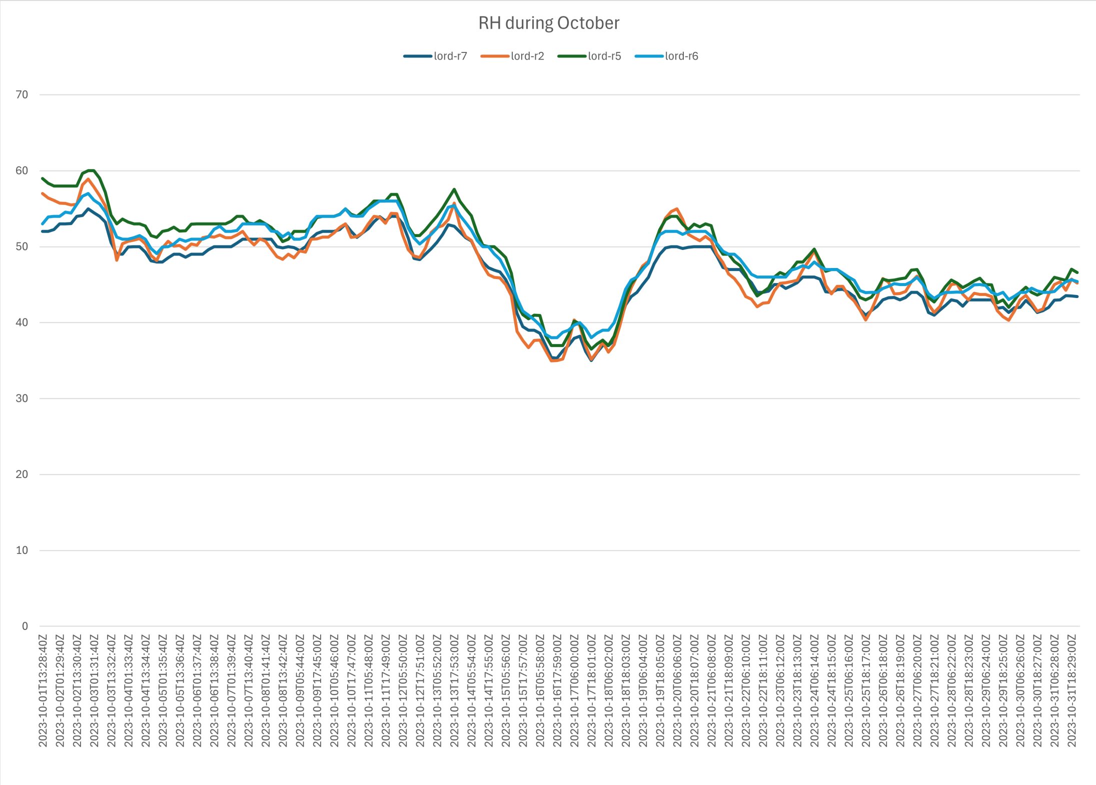


Figure 4.6: RH level disruption during October

4.5 Impact of Temperature on IAQ and Comfort

Indoor temperature is a key determinant of IAQ and occupant comfort, playing a significant role in health, productivity, and overall well-being. Low indoor temperatures are associated with an increased risk of cardiovascular and respiratory

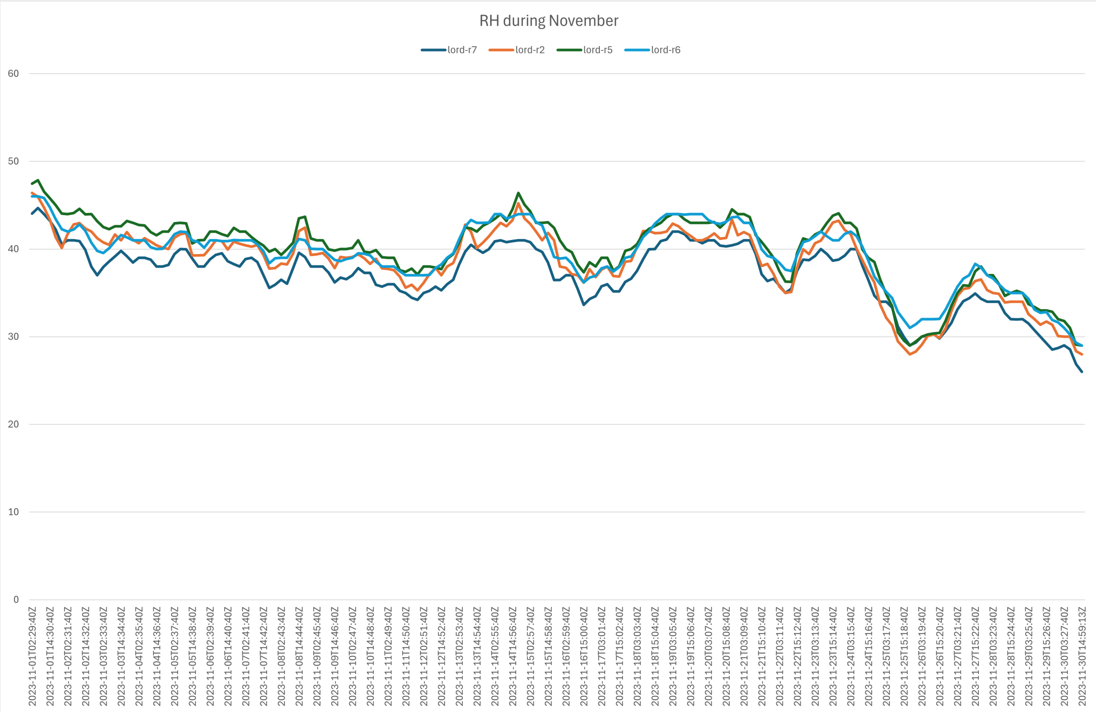


Figure 4.7: RH level disruption during October

illnesses, while excessively high temperatures often lead to discomfort, dry eyes, and respiratory irritation. Research indicates that optimal cognitive performance and productivity are achieved within an indoor temperature range of 22 °C to 24 °C , particularly in temperate or cold climates. Deviations from this range negatively affect learning efficiency, work performance, and general comfort [260].

The WHO's guidelines recommend a minimum indoor temperature of 18 °C in temperate and cold climates to reduce health risks during winter [261]. However, the WHO has yet to establish clear thresholds for maximum indoor temperatures, citing insufficient evidence on their direct health impacts. Despite this, the physiological effects of extreme temperatures on comfort and health are well documented [219, 262]. Recent studies have increasingly focused on the relationship between indoor temperature and cognitive function, and have revealed that maintaining a narrow temperature range enhances work performance and productivity [263, 264]. Although such precision may lead to increased energy consumption, a cost-benefit analysis is necessary to balance TC with energy efficiency [265]. Furthermore, the ideal temperature range varies between regions, which reflects differences in local climate adaptations and occupant expectations [260].

Temperature fluctuations also impact IAQ by influencing CO2 concentrations and energy use. An increase in indoor temperature by 1 °C can cause an increase of 1.2% in CO2 levels and an increase of 8.3% in energy consumption, which highlights the interconnected nature of thermal regulation and air quality [266]. Integrated strategies that optimise temperature control and ventilation can help to address these challenges. For example, maintaining comfortable indoor temperatures while reducing sources of pollution and improving ventilation efficiency can improve productivity by 5% to 10%, as reported by [267]. In contrast, dissatisfaction with indoor temperatures can lead to significant productivity losses, with a 10% increase in dissatisfaction reducing productivity by approximately 1%.

These findings highlight the delicate balance required to effectively manage indoor temperature, IAQ, and occupant comfort. By addressing regional climatic adaptations, improving ventilation strategies, and considering energy efficiency, built environments can achieve optimal TC, improve productivity, and mitigate health risks. Such integrated approaches are essential for creating healthy and sustainable indoor spaces that meet the needs of both the occupants and the environment.

4.5.1 Analysis of Temperature Data

Thermal comfort standards provide a benchmark for assessing the adequacy of indoor temperatures. According to WHO recommendations, a minimum indoor temperature of 18,° C should be maintained in temperate and cold climates to reduce health risks during the winter months [261].

Additionally, research shows that optimal cognitive performance and productivity are typically achieved within an indoor temperature range of 22,° C to 24,° C, especially in temperate or cold climates. Deviations from this range have been linked to reduced learning efficiency, lower work performance, and decreased overall comfort [260].

This subsection presents an analysis of temperature data collected from the teaching office during October and November, specifically during operational hours (9:00 to 17:00). The performance of the air conditioning (AC) system—managed by the building energy management system (BeMS)—was assessed in terms of its ability to maintain adequate thermal conditions.

As illustrated in Figure 4.8, October data revealed noticeable daily fluctuations due to the cyclical operation of the AC system. Temperatures generally ranged between 16 °C and 22 °C, with frequent dips below the lower policy threshold of 19 °C. Although slightly higher temperatures were recorded during core office hours compared to early mornings and weekends, thermal conditions often remained suboptimal. For instance, on 17 October at 10:00, uniform readings of 16 °C were recorded across all monitored zones (Lord-r7, Lord-r2, Lord-r5, and Lord-r6), indicating insufficient heating during the mild autumn season.

This trend persisted into November, as shown in Figure 4.9, with temperature readings predominantly ranging from 16 °C to 20 °C. The system repeatedly failed to maintain the minimum acceptable indoor temperature, especially in response to colder external conditions. On 26 November at 11:20, all sensors again recorded 16 °C, reinforcing the AC system's inability to achieve the minimum thermal standard of 19 °C.

Prolonged exposure to indoor temperatures below the WHO-recommended minimum of 18 °C presents substantial health concerns. Research by Wolkoff et al. [260] shows that low indoor temperatures elevate the risk of respiratory and cardiovascular conditions. In addition to health implications, suboptimal thermal conditions can adversely impact comfort, productivity, and cognitive performance [263, 264].

These findings highlight the underperformance of the current AC system during colder months and the necessity for intervention. System recalibration, enhanced real-time monitoring, dynamic responsiveness to external weather, or the integration of supplemental heating could help maintain indoor temperatures within the recommended 19 °C to 25 °C range. Ensuring thermally stable conditions is essential not only for health and well-being but also for maintaining overall IAQ and occupant satisfaction.

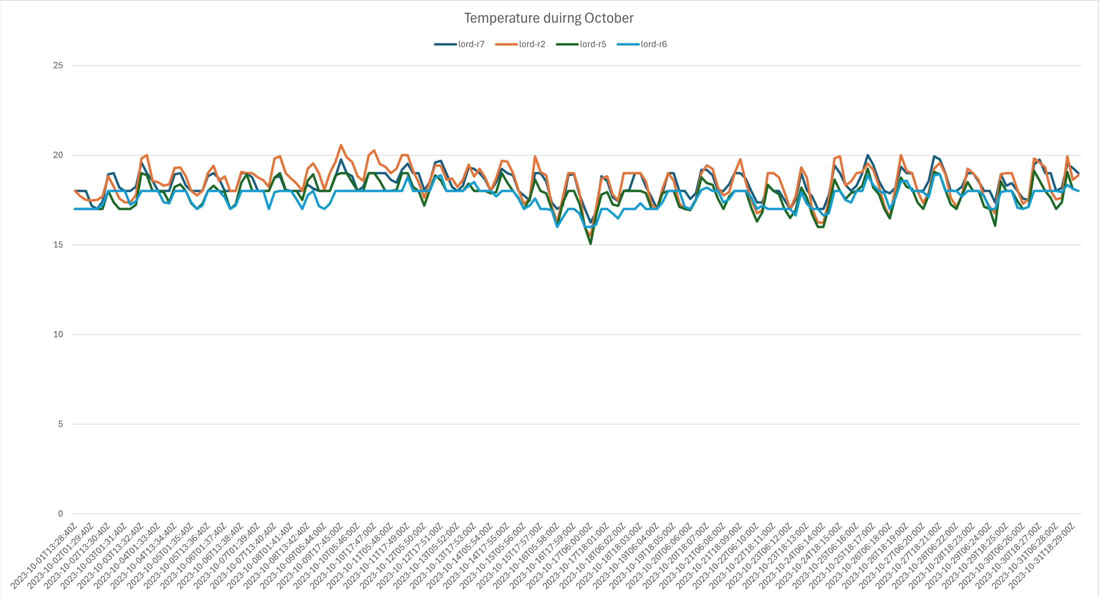


Figure 4.8: Temperature level disruption during October

4.6 Impact of Particulate Matter (PM2.5 and PM10) on Air Quality and Comfort

Airborne PM significantly affects IAQ and poses serious health risks to building occupants. PM consists of microscopic solid particles or liquid droplets, which are

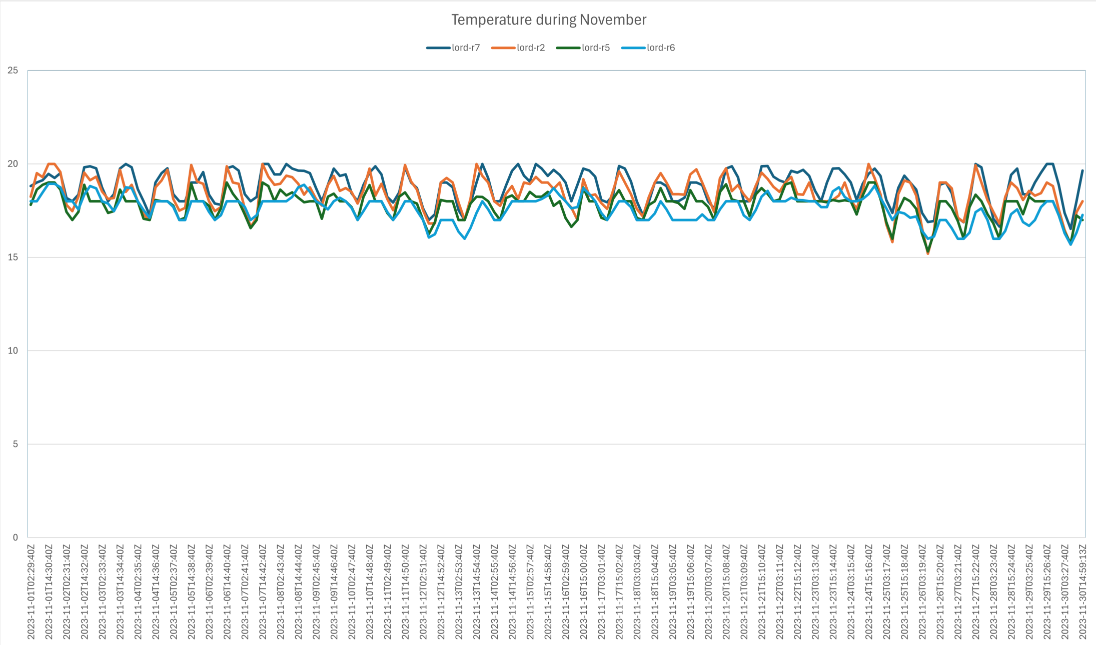


Figure 4.9: Temperature level disruption during November

categorised by size into PM10 (particles smaller than 10 µm) and PM2.5 (particles smaller than 2.5 µm) [268]. Among these, PM2.5 is particularly hazardous due to its ability to penetrate deeply into the respiratory system, reach the alveoli, and even potentially enter the bloodstream. Prolonged exposure to these fine particles has been linked to respiratory and cardiovascular diseases, as well as to reduced cognitive performance and productivity [269, 270].

The sources of PM in indoor environments are diverse, stemming from both outdoor and indoor activities. Outdoor PM often originates from vehicle emissions, industrial processes, and biomass burning and infiltrates buildings through their ventilation systems and natural openings [271–273]. Indoor PM can be generated by activities such as cleaning, cooking, and the use of combustion appliances. This dual source nature complicates PM management because outdoor PM ingress and indoor generation can interact to elevate concentrations within enclosed spaces.

The relationship between CO2 and PM concentrations adds another layer of complexity to IAQ management. Although CO2 is generated predominantly by human respiration and serves as an indicator of ventilation effectiveness, PM concentrations are influenced by both outdoor infiltration and indoor activities. A study by [274] has revealed that increasing ventilation to lower CO2 levels can inadvertently raise indoor PM levels when outdoor air contains high PM concentrations. This trade-off is particularly evident in naturally ventilated spaces, where outdoor pollutants can exacerbate indoor PM levels [274]. In contrast, inadequate ventilation in spaces with high indoor PM sources can increase both CO2 and PM levels, further deteriorating IAQ.

PM2.5 poses a greater challenge due to its association with severe health impacts. Research highlights that exposure to high concentrations of PM2.5 increases the risk of respiratory infections, inflammation, and other chronic diseases [270]. Therefore, managing indoor PM2.5 and PM10 concentrations requires a balanced approach. Effective strategies include incorporating HEPA filters into AC systems, timing ventilation during periods of lower outdoor PM concentrations, and reducing indoor sources of PM through proper home maintenance and controlled use of appliances.

Addressing PM is essential to ensure healthy indoor environments. By mitigating PM concentrations while maintaining adequate ventilation for CO2 control, building managers can achieve better IAQ and occupant comfort. A comprehensive approach that considers the interaction between the sources of PM, the ventilation strategies, and the behaviour of the occupants can help to minimise health risks and promote well-being in indoor spaces.

4.6.1 Importance of Monitoring Particulate Matter

Monitoring PM is critical due to its serious health implications, including respiratory, cardiovascular, and neurological disorders [275, 276]. Elevated PM levels, particularly during the heating seasons, can frequently exceed safe thresholds, which contributes to the degradation of IAQ and increases the health risks of the occupants [275]. Although continuous monitoring is essential to assess these risks, traditional instruments for PM measurement are often bulky, expensive, and unsuitable for widespread deployment [277]. The development of portable real-time monitoring systems equipped with electronic sensors has emerged as a cost-effective and scalable solution, allowing more frequent and precise evaluations of PM2.5, PM10, and related IAQ parameters [277].

Certain environments, such as construction sites, demonstrate the need for robust PM monitoring protocols, with PM levels that have been reported to exceed regulatory limits 100 to 1,000 times [278]. However, existing monitoring practices often lack standardisation in terms of metrics, techniques, and sampling locations, which results in inconsistent IAQ assessments [278]. Targeted monitoring is necessary because average PM measurements can obscure the risks associated with short-term exposure to elevated concentrations, which have pronounced health effects [276].

The WHO has established stringent guidelines for PM concentrations, recommending a 24 hour mean of 25 $\mu g/m^3$ and an annual mean of 10 $\mu g/m^3$ for PM2.5, and 20 $\mu g/m^3$ (24 hour) and 50 $\mu g/m^3$ (annual) for PM10 (WHO Regional Office for Europe, 1998) [131]. However, it has been shown that PM levels in office environments often approach or exceed these limits. For instance, observed concentrations of 15 $\mu g/m^3$ for PM2.5 and 45 $\mu g/m^3$ for PM10 highlight the need for interventions to improve IEQ and protect occupant health [279].

Standardised and continuous PM monitoring practices are essential to identify high-risk environments, evaluate the performance of ventilation and filtration systems, and implement targeted mitigation measures. Advanced real-time monitoring technologies provide a practical solution to overcome the limitations of traditional methods, which enables more accessible and precise IAQ assessments. By using these technologies and adhering to standardised protocols, building managers can improve occupant safety and well-being, particularly in office environments where exposure to PM can have long-term health impacts.

4.6.2 Analysis of PM2.5 and PM10 Data

PM concentrations are evaluated against health-based thresholds established by the World Health Organization (WHO). According to WHO guidelines, the recommended 24-hour mean for PM2.5 is 25 $\mu g/m^3$, with an annual mean of 10 $\mu g/m^3$. For PM10, the corresponding limits are 50 $\mu g/m^3$ (24-hour mean) and 20 $\mu g/m^3$ (annual mean) [131]. These benchmarks serve as reference points for evaluating the potential health risks associated with short- and long-term exposure to airborne particulates.

This subsection analyses the concentrations of PM2.5 and PM10 in the teaching office throughout October and November, providing insights into indoor air quality (IAQ) dynamics and their implications for occupant health and comfort. The findings highlight key temporal patterns and inform targeted recommendations for IAQ improvement.

Figure 4.10 illustrates fluctuations in PM2.5 levels during October, revealing sporadic peaks that align with high-occupancy periods. These variations suggest that occupant activities—such as movement, dust resuspension, and cleaning—play a significant role in elevating PM concentrations. Notable spikes were recorded in mid-October, with levels exceeding 3.5 $\mu g/m^3$, likely influenced by seasonal changes or specific events such as maintenance activities.

In November, Figure 4.11 shows increased variability in PM2.5 levels, with more pronounced peaks than in the previous month. A particularly significant surge occurred on 26 November, when concentrations exceeded 6 $\mu g/m^3$. This deviation from the typical range may be attributed to changes in ventilation patterns, infiltration of outdoor pollutants, or intensified indoor activity. These observations underscore the complex interaction between indoor sources and external environmental factors, warranting further investigation into their combined effects on IAQ.

Figure 4.12 presents PM10 concentrations during October, showing intermittent peaks, with values reaching $5\,\mu g/m^3$ on 9 October. While these levels remain below international health thresholds, even temporary elevations can degrade IAQ and pose risks for individuals with respiratory sensitivities. Moreover, these spikes contribute to cumulative exposure over time, particularly in frequently occupied environments.

In November, PM10 trends followed a similar pattern to PM2.5, with sporadic elevations illustrated in Figure 4.13. A notable peak was recorded on 26 November at 14:51, with concentrations approaching $9\,\mu g/m^3$. This increase may be linked to external pollution events—such as nearby construction—or to indoor sources like evening cleaning operations. Although these peaks were short-lived, they represent moments of air quality degradation that merit further scrutiny and mitigation.

Overall, PM2.5 and PM10 concentrations during the monitoring period remained within WHO-recommended limits, reflecting generally good indoor air quality in the office space. However, the occurrence of episodic peaks—particularly during high-occupancy periods or due to external pollution—highlights the need for continuous monitoring and responsive mitigation strategies. These findings reinforce the importance of maintaining robust IAQ management practices to safeguard occupant health and comfort.

4.7 Discussion

The analysis of IAQ parameters, including CO2 concentrations, temperature, RH, and PM (PM2.5 and PM10), highlights the strengths and limitations of the

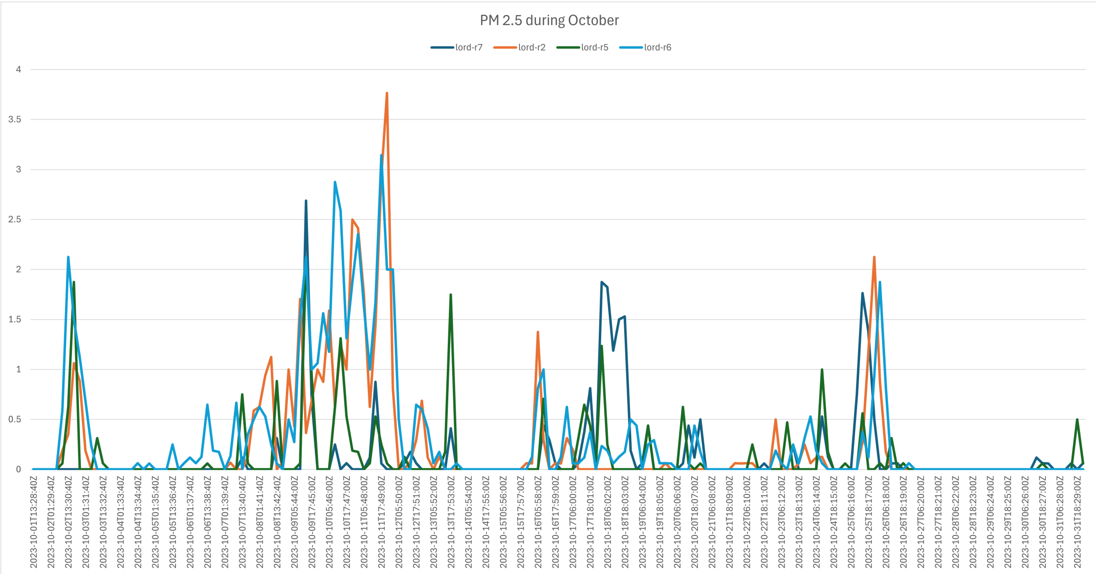


Figure 4.10: PM2.5 level disruption during October

existing ventilation system, which relies primarily on an AC system. Although this system provides some level of TC, its reliance on recirculated air presents significant challenges in maintaining IAQ during periods of high occupancy. This discussion will explore the implications of these findings, focussing on how the AC system influences each parameter and offering targeted recommendations for improvement.

4.7.1 CO2 as an Indicator of Ventilation and Infection Risk

The analysis revealed that CO2 concentrations frequently exceeded 700 ppm during peak office hours, a threshold associated with inadequate ventilation and increased risk of infection. For example, levels as high as 1130 ppm were recorded during high occupancy periods, which underscores the limitations of the AC system in ensuring adequate air exchange. Because the AC system recirculates the indoor air without introducing fresh air, it does not dilute CO2 or other airborne contaminants effectively during these periods.

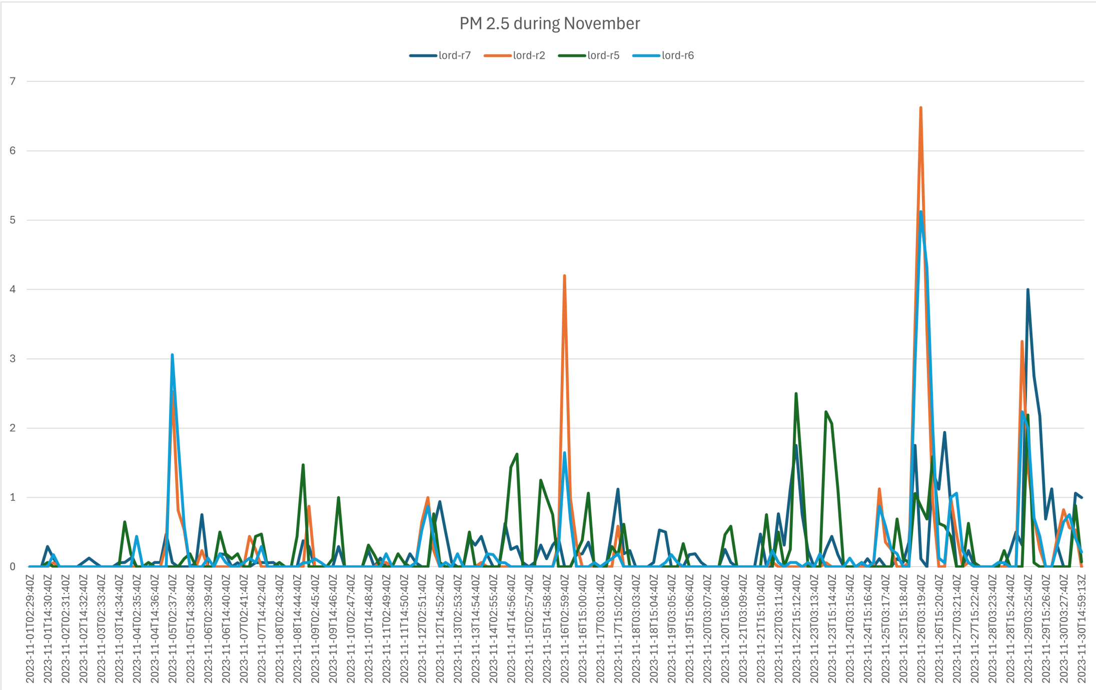


Figure 4.11: PM2.5 level disruption during November

In contrast, CO2 levels consistently dropped below 700 ppm during off-hours, which indicates that reduced occupancy allows the system to maintain IAQ. However, this highlights its reliance on human absence rather than efficient ventilation mechanisms to reduce CO2 concentrations. These findings emphasise the need for improved ventilation strategies, particularly during work hours. A mixed ventilation system, which combines natural ventilation with air exchange, could address this shortfall by introducing fresh air to dilute CO2 and improve IAQ.

Furthermore, implementing real-time CO2 monitoring and adaptive controls could enable ventilation adjustments based on occupancy and activity levels, ensuring safer indoor conditions while balancing TC.

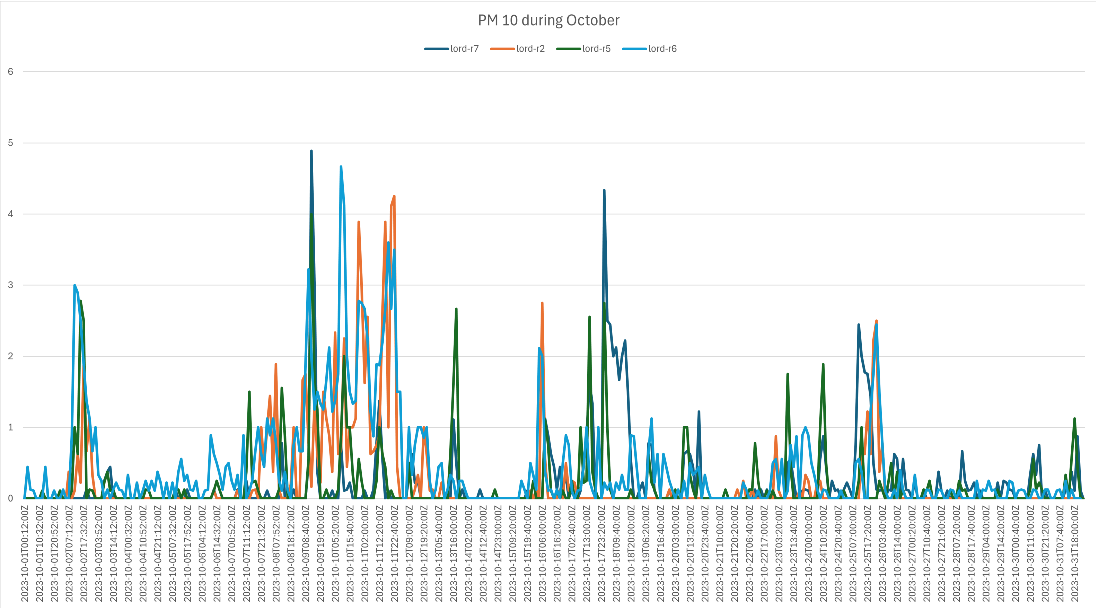


Figure 4.12: PM10 level disruption during October

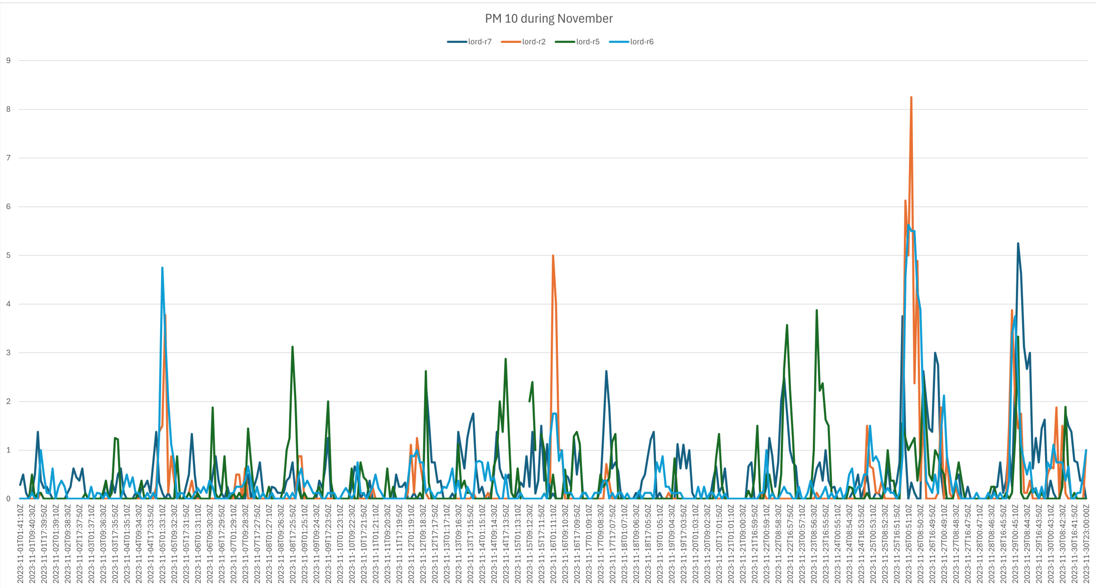


Figure 4.13: PM10 level disruption during November

4.7.2 Temperature Fluctuations and Thermal Comfort

The temperature data demonstrated that indoor temperatures fluctuated between 16 °C and 22 °C, with readings frequently falling below the 19 °C institutional threshold and the 18 °C minimum recommended by the WHO [261], as previously detailed in Section 4.5.1. These findings highlight the AC system's tendency to prioritise energy efficiency over consistent thermal regulation, particularly during low-occupancy periods such as early mornings and weekends.

As discussed in Section 4.5.1, while slightly higher temperatures were recorded during core office hours, the system consistently failed to deliver adequate thermal comfort, especially in response to colder outdoor conditions. This is further supported by observations in Section 4.3.2, which note the system's reliance on air recirculation, thereby limiting the introduction of fresh air and the removal of indoor pollutants.

Although the system provides moderate thermal comfort during active periods, its operational strategy contributes to broader IAQ concerns. The use of recirculated air without adequate ventilation undermines both comfort and air quality, potentially increasing health risks—particularly for vulnerable occupants.

To address these issues, integrating dynamic heating strategies that adjust based on real-time occupancy and environmental inputs could enhance thermal comfort. Additionally, as recommended in earlier sections, particularly Section 4.3.2, a mixed ventilation approach that combines mechanical and natural ventilation may better balance temperature control with improvement of IAQ, fostering a healthier and more comfortable indoor environment.

4.7.3 Relative Humidity and Its Impact on Indoor Air Quality and Infection Risk

The RH data showed that levels generally remained within the recommended range of 40% to 60%, but occasionally dropped to 27% during November. Low humidity levels, particularly below 40%, are associated with increased survival rates for viruses such as COVID-19, as well as a higher transmission potential

[257, 258]. These findings highlight the limitations of the AC system, which lacks integrated humidity control and can exacerbate low levels of RH during the colder months.

Maintaining optimal RH levels is critical to reducing infection risks and improving occupant comfort. To address this problem, mixed ventilation, which combines AC and natural ventilation, offers a promising solution to mitigate humidity issues. By allowing the controlled introduction of outdoor air, mixed ventilation can help balance indoor humidity levels, especially when outdoor conditions fall within an acceptable range. However, during periods of low outdoor humidity, additional interventions, such as portable humidifiers or integrated humidification systems in the AC setup, may be necessary to maintain RH within the optimal range.

Real-time RH monitoring should also be used to track fluctuations and dynamically guide ventilation adjustments. CFD simulations can further provide insight into airflow and humidity distribution, which would help to identify zones that are prone to low RH levels and enable targeted solutions to stabilise humidity levels across the office environment. Maintaining optimal levels of RH is essential not only for occupant comfort but also to minimise infection risks associated with dry indoor air.

4.7.4 Particulate Matter and Air Quality Concerns

The analysis of PM2.5 and PM10 concentrations revealed occasional spikes during periods of high activity or external pollution, such as the peak of PM2.5 above $6\,\mu g/m^3$ on 26 November. Although overall concentrations remained within safe limits, these spikes underscore moments of air quality degradation that the AC system cannot address effectively. The AC system recirculates indoor air without advanced filtration or exchange of fresh air, which limits its capacity to handle

PM introduced by human activity or external sources.

Mixed ventilation can provide a viable solution to improve PM management [280]. By combining AC with controlled natural ventilation, it can improve air exchange rates, diluting indoor particulate concentrations while allowing more responsive IAQ management. However, care must be taken not to introduce outdoor PM during periods of high external pollution. Real-time monitoring of indoor and outdoor PM levels can guide natural ventilation timing, which would ensure that air exchange occurs when outdoor conditions are favourable.

4.8 Conclusion

Through a comprehensive analysis of CO2 concentrations, temperature, RH, and PM in a teaching office environment, the findings revealed that elevated CO2 levels were closely associated with periods of high occupancy and inadequate ventilation, particularly during peak office hours. CO2 concentrations frequently exceeded the 700 ppm threshold, aligning with previous studies that link poor ventilation to increased airborne transmission risk.

In direct response to RQ2, the results confirm that CO2 levels can serve as a reliable and practical indicator of IAQ and potential infection risk. While CO2 is not a direct measure of airborne pathogens, its accumulation reflects exhaled breath and, consequently, the potential build-up of infectious aerosols. Real-time CO2 monitoring can therefore act as an early-warning tool to detect ventilation inadequacies and prompt timely interventions.

The chapter also evaluated the limitations of relying solely on the existing AC system, which primarily recirculates indoor air with minimal fresh air supply. To address this, the integration of natural ventilation alongside the AC system—in the form of a mixed-mode ventilation strategy—was proposed as a means of maintaining acceptable CO2 levels while preserving thermal comfort.

In addition, this chapter contributes to the overall research by providing empirical evidence supporting the use of CO_2 as a surrogate indicator for ventilation effectiveness and airborne infection risk. It demonstrates the value of IAQ monitoring using environmental sensors and identifies critical limitations in the current AC-driven ventilation setup. These findings directly inform the CFD modelling scenarios and ventilation strategies explored in Chapters 5, 6, and 7, forming a foundation for designing healthier, better-ventilated office environments.

Chapter 5

Air Recirculation Systems: Air Conditioners

5.1 Introduction

Building upon the findings of Chapter 4, which identified limitations in existing AC ventilation systems, this chapter directly addresses **Research Question 3** by evaluating the performance of a four-way ceiling cassette air conditioning (AC) system, focussing on its effectiveness in regulating airflow, maintaining thermal comfort, and mitigating airborne infection risks. The analysis uses CFD simulations to examine airflow distribution patterns, thermal comfort variations, and aerosol dispersion dynamics under AC-driven ventilation.

The role of HVAC systems in the dispersion of airborne pathogens, particularly SARS-CoV-2, remains a topic of debate in the literature [281]. HVAC systems have been implicated in facilitating airborne virus transmission because they can redistribute virus-laden aerosol particles that remain suspended in the indoor air for extended periods [282], unlike larger respiratory droplets that settle quickly near their emission source [283].

Epidemiological investigations have produced mixed findings on the influence of HVAC and AC systems on SARS-CoV-2 transmission. One study has suggested that a shared ventilation shaft in an apartment building facilitated interfloor transmission through aerosol transport, which highlights the potential for passive airborne dispersion [95]. Another notable case from a restaurant in Guangzhou, China, involved an AC system in viral spread due to low ventilation rates (0.7 ACH) and high directional airflow, which dispersed viral aerosols across multiple tables [284]. However, subsequent environmental sampling found no trace of SARS-CoV-2 at the inlets and outlets of the AC unit, which raises uncertainty as to whether air recirculation or simply air flow direction played a more significant role in transmission [284].

Further studies have demonstrated the presence of SARS-CoV-2 RNA within HVAC components, which suggests that viral particles can accumulate in ventilation systems. In an Oregon hospital, SARS-CoV-2 RNA was detected in 25% of samples from air handling units (AHUs), with the highest concentrations found in prefilters (35%), final filters (16. 7%), and supply air dampers (20.8%) [115]. However, the detection of viral RNA does not confirm the presence of infectious virus particles because genetic material can persist beyond viral viability [285]. In addition, no confirmed transmission cases were directly linked to HVAC-mediated aerosol dispersion in these studies. Other investigations, such as the Diamond Princess cruise ship outbreak, have yielded contradictory interpretations, with some researchers suggesting the involvement of HVAC in viral spread [286], while others failed to find strong evidence of transmission between rooms [287].

Although the role of HVAC systems in the transmission of SARS-CoV-2 remains inconclusive, historical outbreaks of respiratory viruses have demonstrated their potential to influence the spread of the pathogen. During the 2002 to 2003 SARS-CoV-1 outbreak, hospital transmission was a major factor in the number of cases, and airflow patterns within HVAC systems contributed to a superspread event in a Hong Kong hospital where more than 140 individuals were infected [288]. Similarly, during the 2015 Middle East Respiratory Syndrome (MERS) outbreak, a viable virus was detected in an air handling system exhaust damper, which further supports the hypothesis that airflow from the HVAC can impact the spread of airborne pathogens [289].

5.1.1 Air Recirculation and Infection Risk

Most room-level AC systems rely on air recirculation rather than the introduction of fresh outdoor air, which potentially increases the risk of accumulation of airborne pathogens in enclosed spaces. Unlike centralised HVAC systems that incorporate HEPA or minimum efficiency reporting value (MERV), commonly used AC units, including split ACs, cassette ACs, and FCUs, often lack sufficient filtration capabilities to effectively capture virus-laden aerosols [240]. As a result, infectious aerosols can persist within the indoor environment, repeatedly recirculating and increasing occupant exposure, particularly in areas with poor ventilation [290, 291].

Understanding the interaction between AC-induced airflow and respiratory particle dispersion is critical to minimise cross-infection risks in shared indoor spaces. CFD has become an essential tool in this field, allowing researchers to analyse airflow dynamics, optimise ventilation strategies, and identify high-risk zones for airborne pathogen exposure [292]. CFD simulations have been widely used to evaluate mitigation strategies, including mechanical ventilation configurations [293–295], natural ventilation approaches such as window opening strategies [296–298], the effectiveness of physical barriers such as glass partitions [299, 300], and the role of standalone air purifiers in reducing indoor contaminant concentrations [188, 301].

Despite advances in ventilation research, the role of room-level air recirculation systems (RRSs) in infection control remains insufficiently studied. These systems, including wall-mounted air conditioners (WMACs), floor-mounted air conditioners (FSACs), and four-way cassette air conditioners (WCACs), are widely used in classrooms, offices, and restaurants, yet their specific influence on airborne virus transmission is not well understood [302–304]. Although previous studies have evaluated AC performance primarily in terms of TC and perceived air quality [305–307], a quantitative evaluation of airflow distribution in relation to infection risk remains largely unexplored.

5.1.2 Chapter Objectives

The primary objective of this chapter is to evaluate the performance of the WCAC System in regulating airflow, maintaining TC, and mitigating risks of airborne infection in office environments. Despite its widespread adoption in commercial buildings, research on the air distribution efficiency of ceiling cassette systems and their role in improving IAQ remains limited. This study aims to address this gap by leveraging CFD simulations to analyse the effectiveness of the system ventilation under real-world operating conditions.

To achieve this, the following key objectives are outlined:

- Analyse airflow distribution patterns generated by the ceiling cassette AC system, assessing its ability to achieve uniform air circulation, prevent stagnation zones, and enhance overall ventilation efficiency.
- Evaluate the variations in temperature and RH within the office space to determine their impact on thermal stability and occupant comfort under AC-driven ventilation.
- Assess TC levels using PMV and PPD indices, ensuring compliance with ASHRAE Standard 55 and identifying potential discomfort zones.
- Investigate aerosol dispersion patterns during coughing and sneezing events to quantify the risk of airborne virus transmission within an AC-driven ventilation setting and determine potential exposure hotspots.

- Compare the performance of AC with the standards of ASHRAE 55, EN 16798, and ISO 7730 for TC to ensure that the system meets the recommended ventilation efficiency criteria.
- Identify an optimised ventilation strategy that improves IAQ, reduces thermal discomfort, and improves airflow efficiency, contributing to the development of healthier and safer office environments.

5.2 Methodology

This chapter employs a CFD simulation approach to evaluate the performance of AC in an open-plan office environment. This study follows a structured methodology to systematically assess airflow behaviour, TC, and aerosol dispersion, ensuring a comprehensive evaluation of IAQ and its implications for occupant health and comfort.

This methodology consists of several key stages, starting with the identification of solver parameters, geometric modelling, and meshing strategies, followed by the definition of boundary conditions. The CFD simulation is then executed to analyse the distribution of air velocity, temperature, RH, occupant TC indices (PMV and PPD), and aerosol dispersion in AC settings. A baseline case study is established and solution convergence is monitored to ensure numerical precision before proceeding to the results analysis and recommendations for ventilation optimisation.

The general research framework is illustrated in Figure 5.1, which describes the step-by-step simulation process.

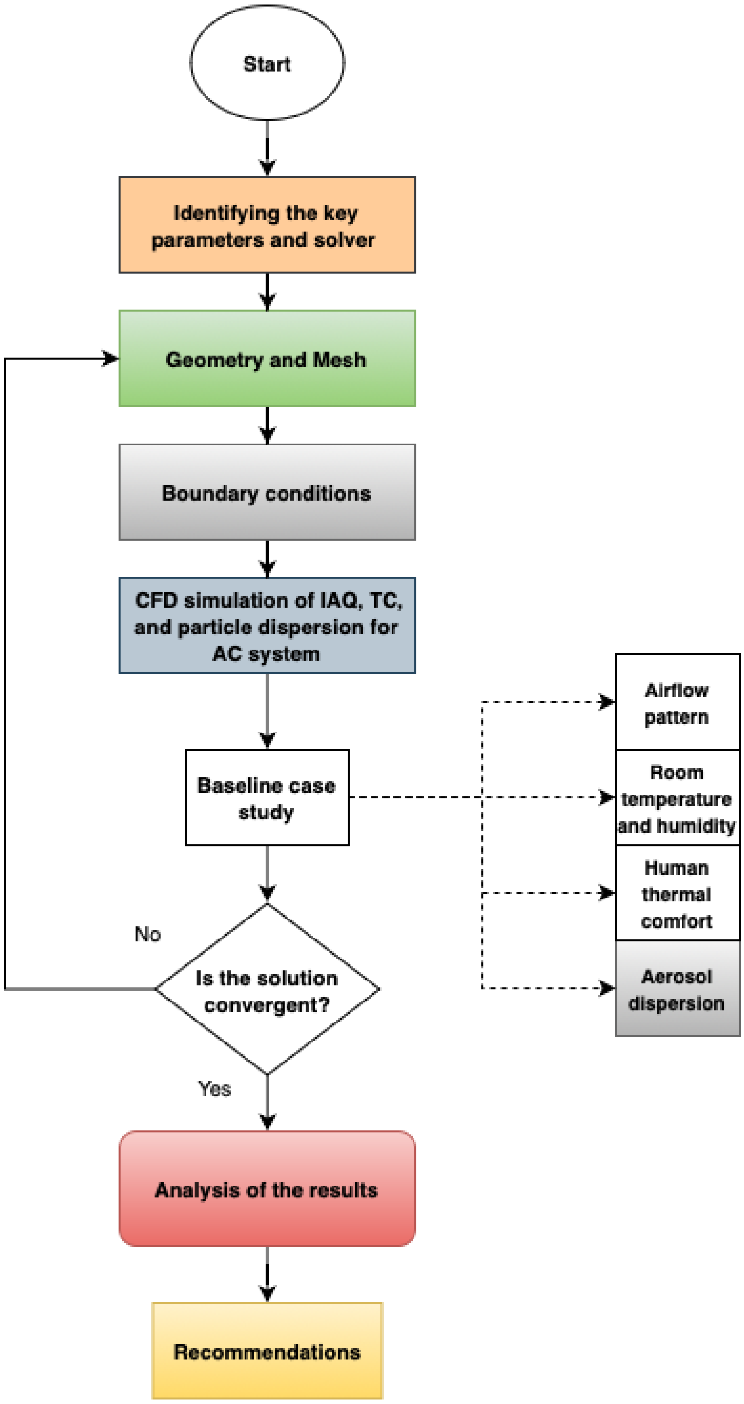


Figure 5.1: Overview of the methodology for AC simulations

5.3 Geometry

This study employs a detailed CFD simulation to assess various ventilation strategies to optimise air quality, TC, and infection risk management in a teaching office environment. The office layout was created using ANSYS DesignModeler® R18.1, ensuring an accurate representation of spatial dimensions, ventilation components, and occupancy distribution. The simulation domain was designed to capture real-world airflow behaviour while maintaining computational efficiency.

The office consists of three distinct zones, each with varying sizes and ventilation conditions. Zone 1 is the largest space, measuring 12 m $\times$ 15 m $\times$ 4 m (720 m^3), while Zone 2 and Zone 3 are smaller offices measuring 6 m $\times$ 5.5 m $\times$ 4 m (132 m^3) and 3 m $\times$ 2.5 m $\times$ 4 m (30 m^3), respectively. Figures 3.5 and 3.6 provide an illustration of the layout and spatial dimensions. The office includes 18 single windows (equivalent to nine double windows), each 2.0 m $\times$ 0.8 m, positioned to facilitate natural ventilation as illustrated in Figure 3.9. Furthermore, the office has two main doors: one remains open, providing access to a hallway and student area, while the other remains closed, limiting airflow exchange (Figure 3.10).

To model AC ventilation, the office is equipped with six four-way cassette air conditioners (Figure 3.11). Five AC units are installed in Zone 1, while one AC unit is present in Zone 2. Zone 3 lacks an AC system, relying on passive airflow through a connecting door. This setup allows for a comparative analysis of ventilation effectiveness across differently ventilated spaces, supporting the study's evaluation of AC, natural, and mixed ventilation scenarios.

The office was originally designed to accommodate up to 13 employees. However, following the onset of the COVID-19 pandemic, flexible and staggered work schedules were implemented, resulting in fluctuations in daily occupancy. According to the teaching office manager, the number of employees present on a typical day has often been around nine. Zone 1 hosts nine employees, Zone 2 houses three employees, and Zone 3 contains one employee. Each employee is assigned a dedicated workstation, including a computer and a printer, which contributes to internal heat loads and localised airflow variations. To assess the risk of infection, four strategic occupant positions (A, B, C, and D), as illustrated in Figure 5.2, were designated as potentially infected individuals within Zones 1 and 2, allowing investigation of aerosol dispersion patterns and the impact of occupant placement on airborne contaminant transport.

Occupants were represented using a simplified human model, which was optimised to balance computational efficiency and anatomical realism, as validated in previous studies [308]. Each model consists of a rectangular torso (0.4 m × 0.3 m × 1.1 m) and a cubic head (0.2 m × 0.2 m × 0.2 m).

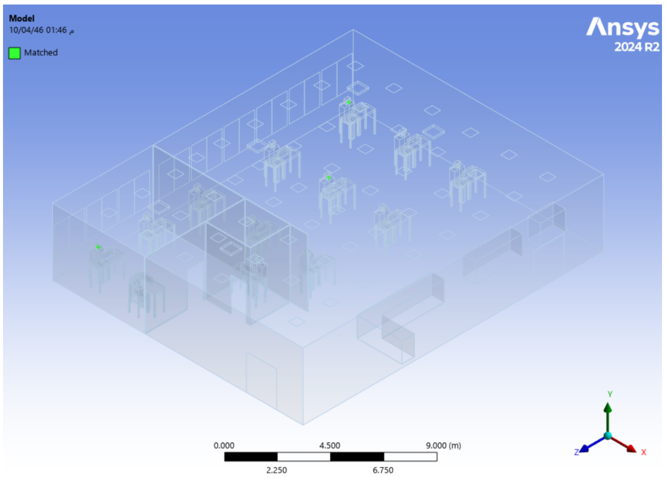


Figure 5.2: Locations of infected individuals

5.4 Modelling Meshing

The computational domain was meshed using ANSYS Meshing® R18.1, employing tetrahedral elements due to their suitability to handle complex and irregular geometries, such as occupants and fine airflow structures. Tetrahedral meshing ensures flexibility while maintaining sufficient resolution in key areas, improving the accuracy of airflow and aerosol dispersion simulations.

To ensure mesh validity and numerical stability, the generated mesh was evaluated using Orthogonal quality which indicates that higher values indicate better conditioned elements. The orthogonal quality distribution of the final mesh is illustrated in Figure 5.3, showing that most elements exhibit high orthogonality, contributing to improved solver convergence.

A grid sensitivity analysis was performed to determine the optimal mesh resolution while maintaining computational efficiency. Since this study employs a discrete phase model (DPM) to track aerosol dispersion, mesh convergence was assessed by monitoring the total aerosol mass retained in the domain after a coughing event.

Three different mesh configurations were tested:

- Mesh 1: 16,557,464 cells (finest resolution).
- Mesh 2: 1,498,482 cells (moderate resolution).
- Mesh 3: 816,650 cells (coarsest resolution).

The aerosol mass in the domain was monitored at 1 and 2 minutes after injection, as summarised in Table 5.1.

The results demonstrate that mesh 2 provides an optimal balance between solution accuracy and computational efficiency. It produced only a 3.05% deviation from the finest mesh (Mesh 1), while significantly reducing computational costs. In contrast, mesh 3 exhibited errors of 16% and 20%, making it unsuitable for high-fidelity simulations.

Based on these findings, Mesh 2 (1,498,482 cells) was selected as the final grid, ensuring accurate particle dispersion predictions while maintaining computational feasibility.

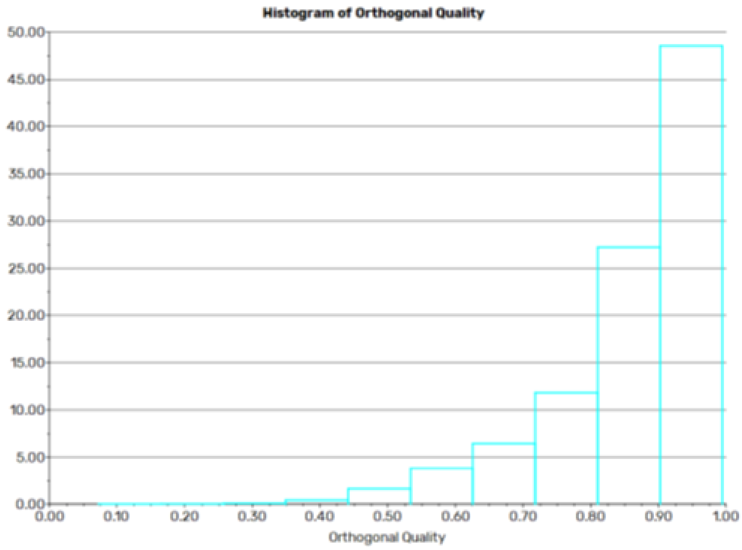


Figure 5.3: Orthogonal quality

	50mm mesh 1	140mm mesh 2	200mm mesh 3
1 minute	0.001143	0.001109	0.001287
2 minute	0.00064	0.00064	0.000771
Errors		-3.05087	16.08396
(%)		0	20.60605

Table 5.1: The selected mesh

5.5 Boundary Conditions

The simulation was carried out under steady-state conditions, with an AC air supply temperature of 19 °C (292.15 K) to maintain a controlled indoor environment. Although coughing and sneezing events are inherently transient phenomena, they were modelled as instantaneous emissions to approximate their aerosol dispersion dynamics without requiring a full transient simulation. This approach ensures computational efficiency while preserving the key transport characteristics of airborne particles.

The AC system was designed to deliver four air changes per hour (ACH) through ceiling-mounted four-way cassette air diffusers, with each inlet supplying air at a mass flow rate of 0.1 kg/s. Although ASHRAE Standard 62.1 recommends a minimum of 4 to 5 ACH for office environments, the selected 4 ACH rate balances energy efficiency and ventilation performance while still providing adequate air exchange for contaminant dilution. The air outlets were modelled using a pressure outlet boundary condition, ensuring continuous airflow discharge while preventing unphysical recirculation effects in the exit regions.

To evaluate the effectiveness of AC in controlling airborne infection risks, six simulation cases were developed, as outlined in Table 7.2. Case 1 establishes a baseline assessment of airflow. room temperature, and RH distribution. Case 2 evaluates the TC implications of the AC by analysing the occupant's thermal perception. Cases 3 to 6 introduce an infected individual seated in different positions (A, B, C, and D), as illustrated in Figure 5.2, to assess aerosol dispersion patterns and infection risks in various spatial configurations. These seating locations were selected to represent typical workstation layouts in an open-plan office, allowing an analysis of how airflow direction, diffuser positioning, and ventilation efficiency influence particle transport and potential exposure risks.

Case No.	Scenario	Infected Source	Notes
1	Scenario 1	None	Assessment of ventilation performance
2	Scenario 1	None	Assessment of TC
3	Scenario 1	A	Assessment of infection risk
4	Scenario 1	B	Assessment of infection risk
5	Scenario 1	C	Assessment of infection risk
6	Scenario 1	D	Assessment of infection risk

Table 5.2: Overview of simulation cases during the AC.

5.6 Results

This section presents the findings of the baseline case study, which examines the effectiveness of AC in regulating IAQ, TC, and airflow distribution. This study focusses on a real AC system, specifically a four-way blow ceiling cassette system, to evaluate its performance under winter conditions. The ventilation system operates through a localised AC unit that supplies air at 19 ° C, with the aim of replicating the operation of real-world HVAC while maintaining adequate air exchange and thermal stability.

Although AC plays a crucial role in controlled indoor environments, the specific performance of four-way blow ceiling cassette systems has been relatively underexplored in the literature. Unlike traditional centralised HVAC systems, this type of ventilation system distributes air through multiple directional outlets, potentially leading to varying airflow patterns, thermal distribution, and pollutant transport dynamics. Therefore, this study seeks to fill a gap in the existing research by analysing its impact on IAQ, airflow homogeneity, and the occupant's TC using CFD simulations and real sensor data validation.

The evaluation focusses on several key parameters, including air velocity patterns, temperature distribution, RH, and TC indices such as the PMV and the PPD. Additionally, to validate the accuracy of the CFD simulations, a two-stage validation process is conducted:

- Validation 1: Comparison of CFD results with published experimental and numerical data for velocity and particle concentration.
- Validation 2: Comparison of CFD results with real sensor data recorded in the office environment under actual operational conditions.

These validation processes ensure the reliability of the numerical simulation before applying it to analyse the AC system in detail.

5.6.1 Validation 1: Validation of the Computational Fluid Dynamics Model Against Experimental Data

The first validation step evaluates the accuracy of the numerical model by comparing the velocity and concentration distributions of particles with both experimental and published numerical results. The experimental study by [236] was used for comparison, where airflow and particle dispersion were measured in a controlled environment.

The CFD validation simulation consists of a rectangular test room (0.4 m × 0.4 m × 0.8 m, width × height × length) with one inlet and one outlet (both 4 cm × 4 cm in size). The inlet velocity is set at 0.225 m/s, and the dispersed particles have a diameter of 10 μm with a density of 14 m^2·kg/m^3. The k-ϵ RNG model was applied for turbulence modelling and air was treated as an incompressible gas. The steady-state flow and turbulence were first solved until convergence, followed by the activation of DPM tracking for unsteady particle dispersion over a simulation period of 360 seconds.

Figure 5.4 shows the comparison of the velocity profile along the centreline of the room between the numerical model (blue points) and the experimental data (orange points). The results indicate a strong agreement between the simulated and experimental velocity values, confirming that the CFD model accurately captures airflow behaviour.

Figure 5.5 presents the particle concentration validation, where numerical results are compared with both experimental measurements (black points with error bars) and published numerical results (red points). The good agreement across all data sets reinforces the reliability of the CFD approach in predicting airborne particle transport.

Velocity and particle concentration were selected as validation metrics because they are the most critical parameters in modelling airborne transmission in indoor

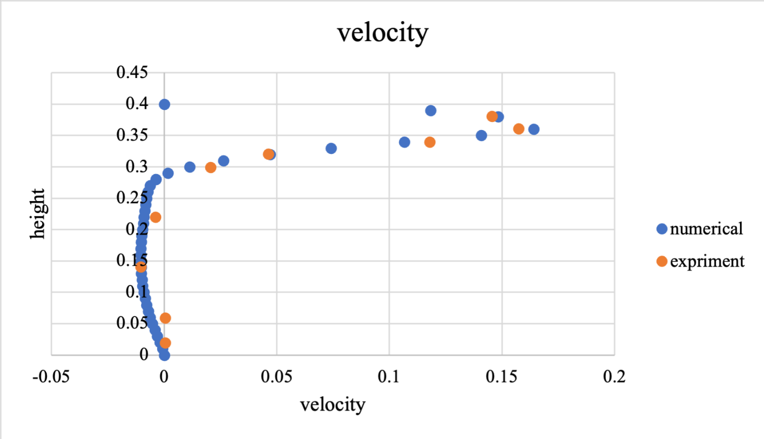


Figure 5.4: Velocity in centre line with the length of 0.2m

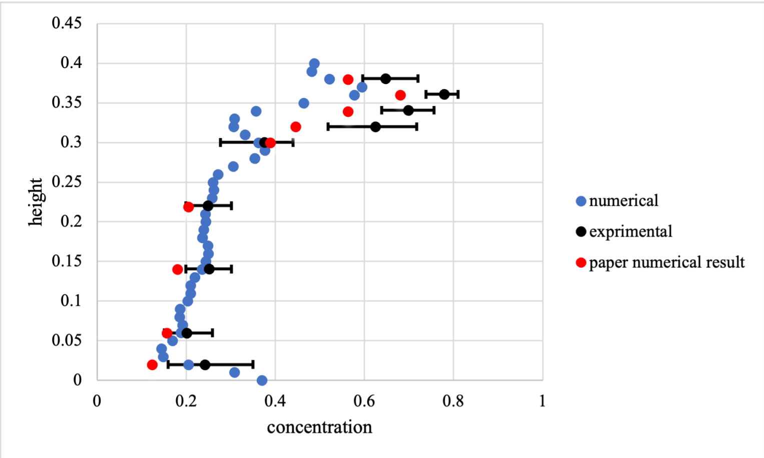


Figure 5.5: DPM concentration in centre line with the length of 0.2m

environments. Velocity validation ensures the model captures airflow dynamics that drive dispersion, while particle concentration validation directly assesses the model's ability to predict exposure risks. Other variables, such as temperature or RH, were not included in this initial validation because the reference study focused solely on airflow and particle tracking, and did not provide those additional measurements. Therefore, the validation approach is consistent with the available benchmark data and aligned with the study's focus on airborne transmission modelling.

5.6.2 Validation 2: Validation of the Computational Fluid Dynamics Model Against Real Sensor Data

To further assess the accuracy of the CFD simulations, real-time sensor data were collected and compared against the simulated results. This validation step is critical to ensuring that the numerical model reliably represents the actual performance of the AC system in regulating the levels of temperature, RH, and CO2. By evaluating the degree of agreement between the measured and simulated values, the credibility of the CFD model can be established in predicting IAQ and TC.

Four environmental sensors were strategically placed within the office space to capture variations in indoor climatic conditions in real operational settings. Two sensors were installed along the side wall of Zone 2 at a height of 2 metres, while the other two were placed along the side of Zone 1 at the same height. Figure 5.6 illustrates the exact location of these sensors. The objective of this configuration was to capture potential differences in airflow, temperature, and air quality distribution influenced by the four-way blow ceiling cassette system.

The recorded sensor data was obtained under normal working conditions, where the presence of the employees varied daily due to flexible work arrangements. This natural fluctuation in occupancy introduced variations in temperature and CO2 concentrations, primarily due to differences in metabolic heat generation and exhalation rates. In contrast, the CFD simulations were conducted under the assumption of full occupancy, representing a worst-case scenario where all workstations were occupied. This approach ensured a standardised comparison between predicted and measured values, while allowing for an analysis of potential deviations arising from occupancy variability.

Comparison between measured and simulated data demonstrated strong agreement in all key parameters, with minor discrepancies primarily attributable to variations in occupancy in the real world and external environmental influences. The temperature values recorded by the sensors were slightly lower than those predicted by the CFD model, probably due to the reduced heat loads from a lower than expected number of occupants in the real scenario. Similarly, CO2 concentrations in the sensor data were slightly elevated, reflecting transient periods of higher occupancy density in the office. Since the CFD model assumed a constant full occupancy scenario, it captured the expected trends in CO2 but exhibited slightly lower absolute values.

RH values showed reasonable agreement between the real data and the CFD model, with minor variations attributed to external weather conditions and differences in ventilation dynamics. The consistency of the RH predictions across both the real and simulated results reinforces the accuracy of the CFD model in replicating the behaviour of indoor moisture under AC.

To quantitatively evaluate the accuracy of the CFD model, the mean absolute percentage error (MAPE) was calculated for each parameter at all of the sensor locations. The results are summarised in Table 5.3 and indicate that the CFD model effectively replicates real-world conditions within an acceptable margin of error. The temperature predictions exhibit an average MAPE of 6.82%, indicating high reliability in thermal modelling. The RH predictions show slightly higher deviations, with an average MAPE of 24 88%, which is probably due to external environmental factors that were not fully captured in the simulation. The CO2 predictions exhibit the lowest error, with an average MAPE of 8. 87%, which confirms the ability of the model to capture air quality variations.

In general, the validation results confirm that the CFD model provides a robust and reliable approximation of indoor environmental conditions under AC. Although there are minor discrepancies, particularly in the RH predictions, the model effectively captures temperature and air quality variations, which makes it a valuable tool to assess IAQ and TC in spaces.

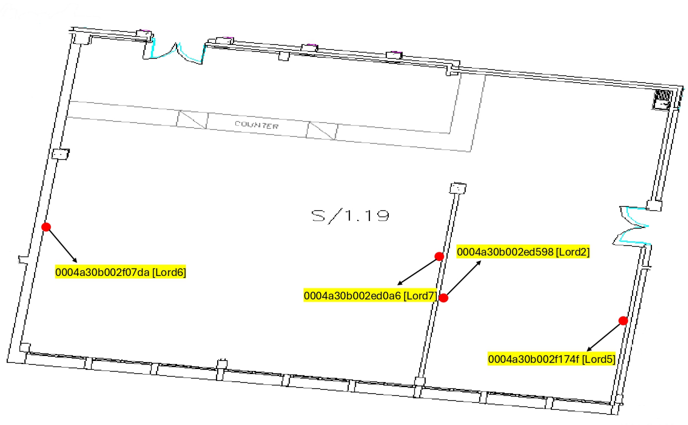


Figure 5.6: CO2 level in the teaching office during AC

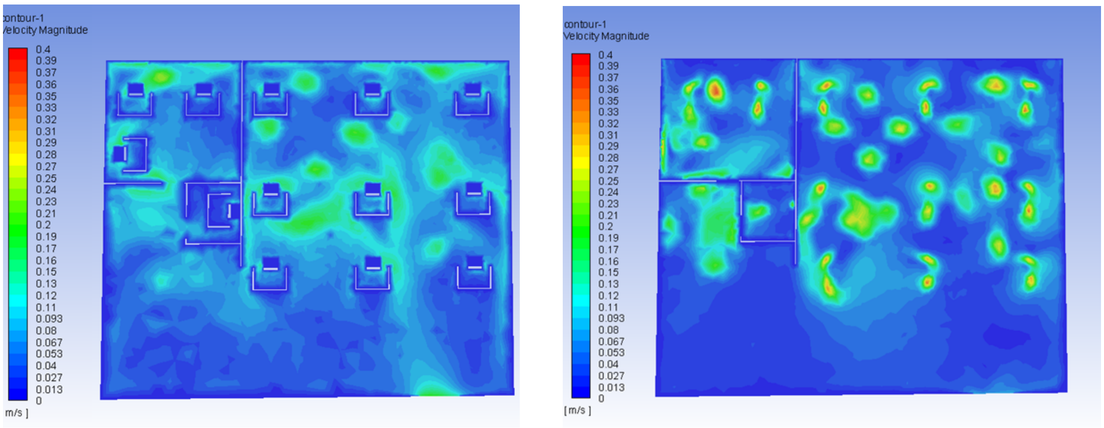
	Temperature			RH			CO2		
sensor	Physical	CFD	MAPE %	Physical	CFD	MAPE %	Physical	CFD	MAPE %
Lord 6	22	23	4.55%	49	60	22.45%	558	480	13.98%
Lord 7	23	24	4.55%	47	60	27.66%	541	471	12.94%
Lord 2	22	24	9.09%	48	65	35.42%	521	498	4.41%
Lord 5	22	24	9.09%	50	56	12%	529	507	4.16%

Table 5.3: Comparison of real data and CFD simulation under AC

5.6.3 Air Velocity Pattern

The air velocity distribution across the three office zones under AC provides critical information on airflow uniformity and the overall efficiency of the four-way blow ceiling cassette system. Figures 5.7 illustrate the airflow characteristics in different zones, highlighting areas of effective ventilation, potential stagnation, and deviations from the optimal air distribution.

From this figure it can be seen that while AC successfully introduces airflow into central zones, it does not fully eliminate stagnant regions, particularly in corners and areas farther from air supply outlets.



(a) z = 1 m (b) z = 2 m

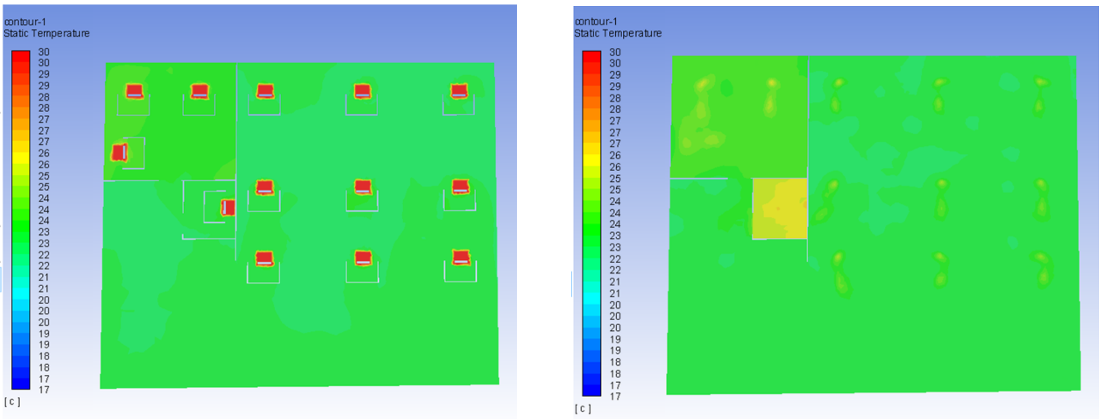
Figure 5.7: Air velocity contour in z direction during AC

5.6.4 Room Temperature and Relative Humidity

The temperature distribution between the three office zones under AC highlights the effectiveness of the system in regulating thermal conditions, while revealing localised variations, as shown in Figures 5.8. This analysis provides insight into variations in TC and the influence of air distribution patterns on temperature stability.

The areas further from the AC outlets in Zone 1 show temperatures around 22 °C, while the seating areas of the occupants in Zones 1, 2, and 3 range between 24 °C and 25 °C. This pattern suggests that although the AC system successfully maintains thermal conditions within acceptable limits, localised heat retention persists in areas with lower air velocity.

In general, the results indicate that the AC system generally maintains indoor temperatures within an acceptable range.



(a) z = 1 m (b) z = 2 m

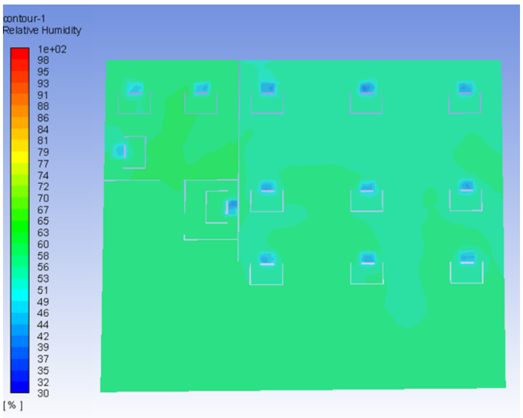
Figure 5.8: Temperature contour in z direction during AC

The distribution of RH in the three AC office zones provides insight into moisture regulation and its interaction with air circulation, occupant presence, and electronic equipment. Figures 5.9 illustrate the spatial variation of RH between different zones, highlighting areas with potential imbalances.

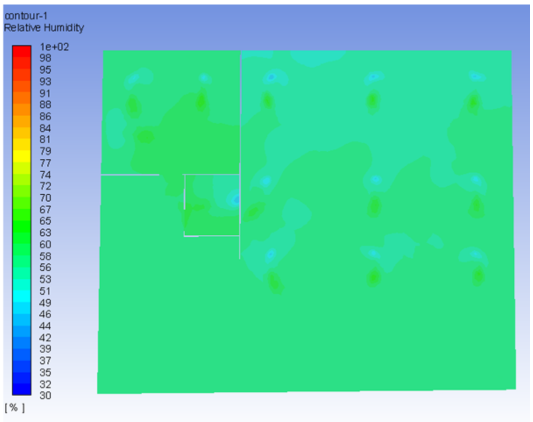
In Zone 1, the seating areas of the occupants maintain an RH of approximately 53%, which is in line with ASHRAE recommended indoor RH levels for TC and air quality. However, in zones farther from the six AC units, the RH levels increase to approximately 60%, indicating reduced airflow penetration and less effective humidity control. The highest levels of RH (above 65%) are observed in Zones 1, 2, and 3, particularly near electronic equipment and areas dense to the occupants, where heat and moisture emissions contribute to the accumulation of local humidity.

5.6.5 Predicted Mean Vote and Predicted Percentage of Dissatisfied

The PMV distribution in the three AC office zones provides valuable information on the TC of the occupant, as shown in Figures 5.10.



(a) z = 1 m



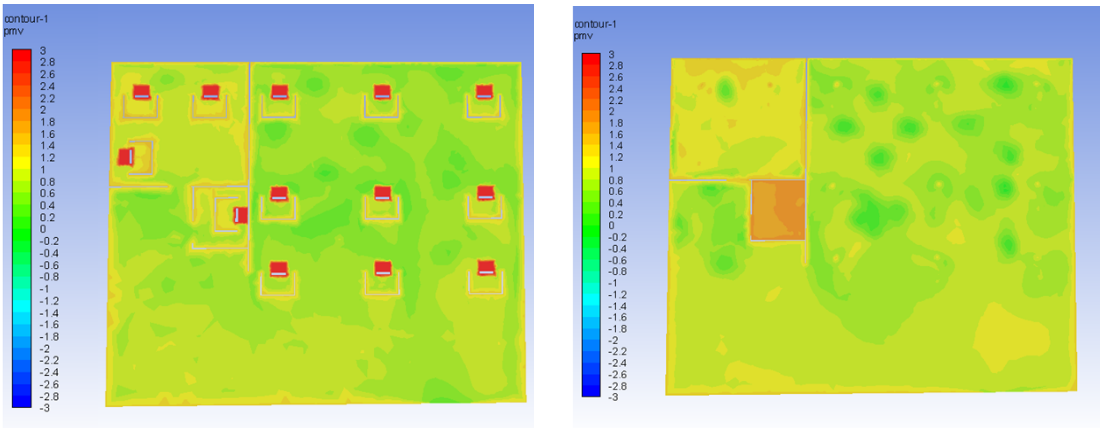
(b) z = 2 m

Figure 5.9: RH contour in z direction during AC

Zone 1 maintains a predominantly neutral to slightly warm thermal environment (PMV: 0 to 1.0), which falls within the acceptable comfort range defined by ASHRAE Standard 55. In contrast, Zone 2 exhibits higher PMV values (1.0 to 1.8), indicating mild discomfort, particularly in areas where heat accumulates near ceilings and walls due to insufficient air circulation. The most significant discomfort is observed in Zone 3, where the PMV values reach 2.2. This suggests pronounced heat retention and inadequate airflow distribution, resulting in a suboptimal thermal environment.

These findings underscore thermal inconsistencies within the office space of the AC system, with Zones 2 and 3 experiencing elevated temperatures that could negatively impact the comfort and productivity of the occupants. According to ASHRAE Standard 55, PMV values exceeding ± 1.0 indicate deviations from optimal TC, strengthening the need for additional cooling interventions in Zones 2 and 3 to improve airflow distribution and mitigate localised overheating.

The PPD values provide a quantitative measure of thermal dissatisfaction among occupants, offering insights into the effectiveness of the AC system in maintaining TC. The distribution of PPD in the three office zones is presented in Figures 5.11.



(a) z = 1 m (b) z = 2 m

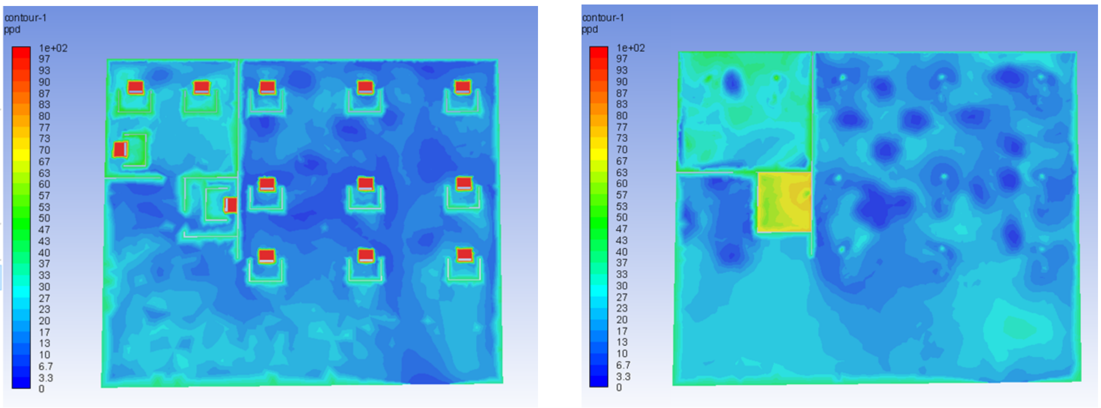
Figure 5.10: PMV contour in z direction during AC

The large office (zone 1) maintains the lowest rate of dissatisfaction, with values predominantly between 20% and 30%, in agreement with acceptable comfort levels under ASHRAE Standard 55. In contrast, Zone 2 exhibits increased dissatisfaction (40%), particularly in the upper regions where airflow is less effective. Zone 3 demonstrates the highest dissatisfaction, with PPD values exceeding 40% to 70%, indicating that AC alone does not maintain TC in this space.

The PPD analysis highlights critical ventilation inefficiencies, particularly in Zones 2 and 3, where dissatisfaction rates exceed the recommended ASHRAE limits. Although AC helps maintain acceptable conditions in Zone 1, targeted interventions are necessary to improve TC in underperforming zones.

5.6.6 Aerosol Dispersion and Infection risk

Coughing is an important contributor to the airborne virus transmission of infectious aerosols in enclosed spaces. This study evaluates the dispersion characteristics of expelled particles under AC conditions. A coughing velocity of 11.8 m/s was applied and the aerosol dispersion was analysed for four infected individuals, each positioned at different locations within the office environment. The objective



(a) z = 1 m (b) z = 2 m

Figure 5.11: PPD contour in z direction during AC

of this analysis is to determine how air flow influences aerosol distribution and potential exposure risks.

Figure 5.12 presents the spatial distribution of aerosols expelled by the first infected individual. The results indicate that aerosols are initially concentrated near the source, but as time progresses the air flow redistributes the particles within the air-conditioned space. The expelled aerosols exhibit forward velocity with an observable dispersion pattern influenced by air circulation patterns. A portion of the aerosols remains suspended in the breathing zone, which increases the potential for short-term exposure among nearby individuals.

Figure 5.12: Particle transmission from the first infected individual during coughing.

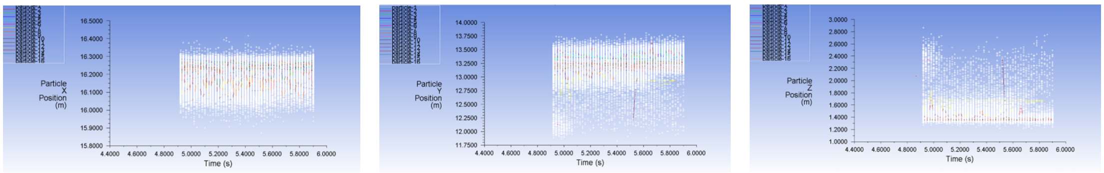
Figure 5.13 illustrates the aerosol dispersion along the X, Y, and Z axes during the coughing event for the first individual, highlighting their dispersion trajectory over time.

Figure 5.13-(a) illustrates that most aerosols expelled along the X axis remain within the 15.9 m to 16.3 m range (indicating a transmission distance of approximately 0.4 m), demonstrating a limited horizontal spread. This indicates that under AC, the coughing event leads to a forward motion with restricted lateral dispersion.

Figure 5.13-(b) highlights that the lateral diffusion of particles along the Y axis ranges from 12.25 to 13.75 m (indicating a transmission distance of approximately 1.5 m), suggesting that airflow induces moderate edgeways spread. The AC system influences this lateral movement, but the particles remain relatively confined within the immediate breathing zone of the infected individual.

Figure 5.13-(c) represents the vertical particle distribution along the Z axis, where the vertical dispersion pattern shows most aerosols remain between 1.2 m and 2.4 m (indicating a transmission distance of approximately 1.2 m), aligning with the

typical seated breathing height of the occupants. This reinforces the potential for exposure among individuals placed near the infected individual.



(a) X direction (b) Y direction (c) Z direction

Figure 5.13: Aerosol dispersion through coughing on X, Y,and Z directions for the first individual during AC.

Figure 5.14 presents the spatial distribution of aerosols expelled by the second infected individual. Initially, the expelled aerosols were highly concentrated near the source, with a dense particle cloud forming immediately after the coughing event. As time progresses, the airflow generated by the AC system redistributes the particles, causing dispersion throughout the surrounding area.

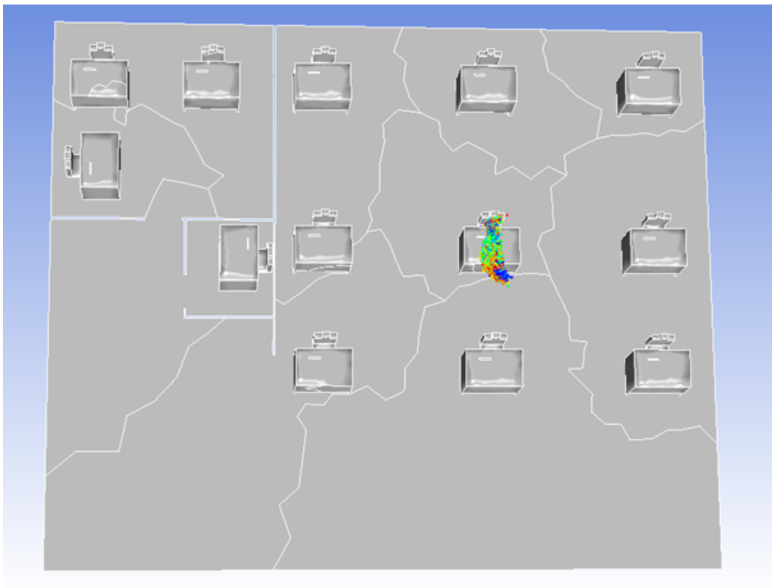


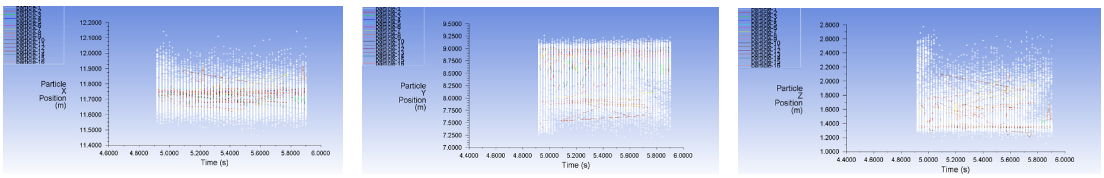
Figure 5.14: Particle transmission from the second infected individual during coughing.

Figure 5.15 illustrates the aerosol dispersion along the X, Y, and Z axes during the coughing event for the second individual, highlighting their dispersion trajectory over time.

Figure 5.15-(a) illustrates that most aerosols expelled along the X axis remain within the 11.6 m to 11.9 m range (indicating a transmission distance of approximately 0.3 m), showing a relatively restricted lateral spread. The air flow influences the horizontal motion of the particles, preventing excessive dispersion beyond this localised range.

Figure 5.15-(b) shows that the lateral diffusion of particles along the Y axis ranges from 7.5 to 9 m (indicating a transmission distance of approximately 1.5 m), indicating that airflow facilitates greater spread in this direction compared to the X axis. This suggests that the surrounding airflow plays a role in extending the reach of aerosols beyond the immediate coughing region.

Figure 5.15-(c) represents the vertical particle distribution along the Z axis, where the vertical dispersion pattern indicates that most aerosols remain between 1.3 and 2.1 m (indicating a transmission distance of approximately 0.8 m), aligning with the typical seated breathing height of the occupants. This reinforces the potential exposure risk for people sitting in close proximity to the infected person because the particles remain within the breathing zone for extended periods.



(a) X direction (b) Y direction (c) Z direction

Figure 5.15: Aerosol dispersion through coughing on X, Y,and Z directions for the second individual during AC.

Figure 5.16 demonstrates the spatial distribution of aerosols expelled by the third infected individual during coughing. The results indicate that the expelled particles initially remain concentrated near the source, with dispersion patterns influenced by the surrounding airflow dynamics of the AC system. Over time, aerosol particles are carried and redistributed by ventilation-induced airflow, highlighting the potential for localised airborne transmission.

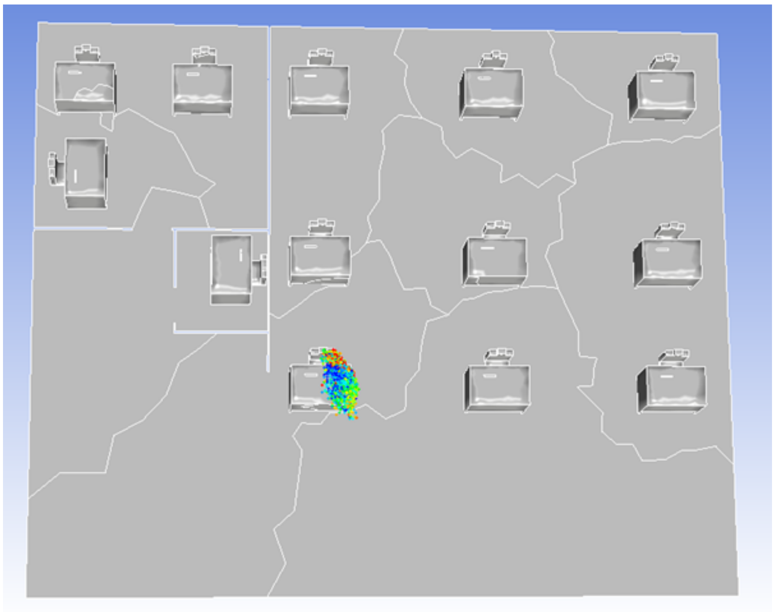


Figure 5.16: Particle transmission from the third infected individual during coughing.

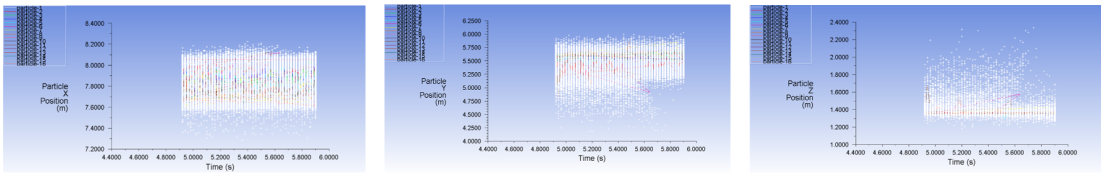
Figure 5.17 illustrates the aerosol dispersion along the X, Y, and Z axes during the coughing event for the third individual, highlighting their dispersion trajectory over time.

Figure 5.17-(a) illustrates that most aerosols expelled along the X axis remain within the range of 7.6 to 8.1 m (indicating a transmission distance of approximately 0.5 m), demonstrating a limited horizontal spread. The initial high coughing velocity propels the aerosols forward, but their dispersion is largely constrained by the AC effects.

Figure 5.17-(b) shows that the lateral diffusion of particles along the Y axis ranges between 5 and 6 m (indicating a transmission distance of approximately 1 m),

indicating moderate side-to-side dispersion. The airflow from the AC system plays a crucial role in particle transport, with some particles showing a slight deviation due to turbulence.

Figure 5.17-(c) represents the vertical particle distribution along the Z axis, where the vertical dispersion pattern indicates that most aerosols remain between 1.3 and 1.7 m (indicating a transmission distance of approximately 0.4 m), aligning with the typical breathing height of seated occupants. This suggests a significant potential for transmission to individuals in close proximity to the infected person, particularly those within the immediate vicinity.



(a) X direction (b) Y direction (c) Z direction

Figure 5.17: Aerosol dispersion through coughing in X, Y,and Z directions for the third individual during AC.

Figure 5.18 illustrates the aerosol dispersion pattern for the fourth infected individual, positioned in Zone 2, where the AC system is operational. The expelled particles exhibit an initial concentrated distribution near the source, with gradual dispersion influenced by the dynamics of the airflow. The AC system affects the spread, redistributing the aerosols in a pattern that is aligned with the prevailing airflow direction.

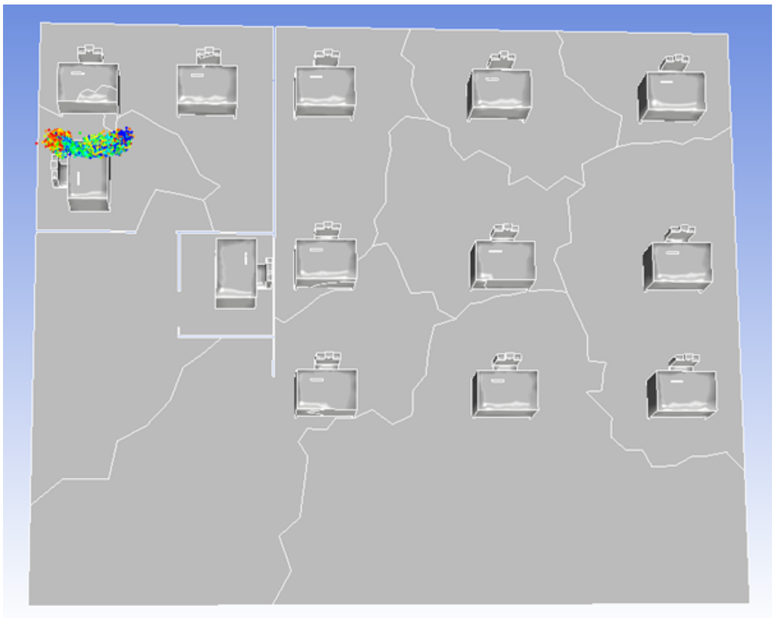


Figure 5.18: Particle transmission from the fourth infected individual during coughing.

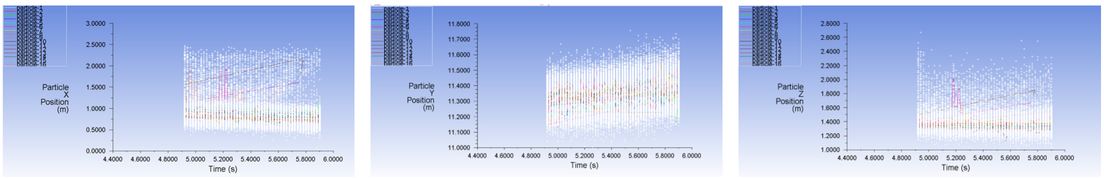
Figure 5.19 illustrates the aerosol dispersion along the X, Y, and Z axes during the coughing event for the fourth individual, highlighting their dispersion trajectory over time.

Figure 5.19-(a) illustrates that most aerosols expelled along the X axis remain confined within the 0.5 to 2.5 m range (indicating a transmission distance of approximately 2 m). The particles exhibit limited forward movement, primarily influenced by the coughing velocity and the airflow pattern induced by the AC.

Figure 5.19-(b) shows that the lateral spread of aerosols along the Y axis occurs within the range of 11.1 to 11.6 m (indicating a transmission distance of approximately 0.5 m). This relatively constrained dispersion suggests that the AC flow directs the particles within a controlled region, reducing the likelihood of significant lateral spread.

Figure 5.19-(c) represents the vertical particle distribution along the Z axis, where the vertical distribution analysis reveals that most aerosols remain within the

range of 1.1 to 2 m (indicating a transmission distance of approximately 0.9 m). This aligns with the typical breathing zones of the occupants in the seated position, emphasising the potential exposure risk for individuals in close proximity.



(a) X direction (b) Y direction (c) Z direction

Figure 5.19: Aerosol dispersion through coughing in X, Y,and Z directions for the fourth individual during AC.

Sneezing is a powerful mechanism for the expulsion of infectious aerosols at high velocity, significantly increasing the risk of rapid airborne virus transmission. Compared to coughing, sneezing generates a more powerful expulsion of particles, resulting in a faster and wider dispersion within an indoor environment. In this analysis, a sneezing velocity of 70 m/s was applied. This study focused on four infected individuals, analysing the spatial and temporal dispersion of particles along the X, Y, and Z directions to evaluate the impact of ventilation strategies on aerosol transmission.

Figure 5.20 illustrates the spatial distribution of aerosols expelled by the first infected individual during sneezing. Compared to coughing, sneezing results in a higher concentration of particles that disperse more widely due to the increased initial velocity. The particles exhibit a strong forward trajectory before interacting with the surrounding airflow, leading to a notable dispersion pattern.

Figure 5.20: Particle transmission from the first infected individual during sneezing.

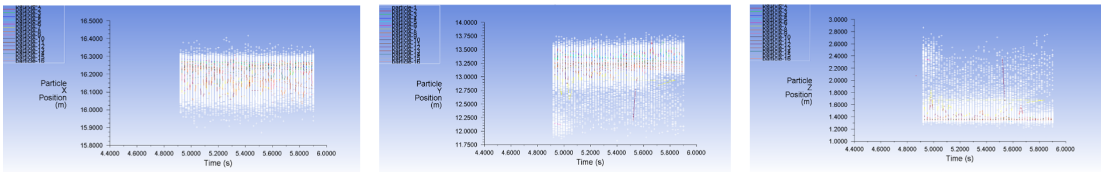
Figure 5.21 illustrates the aerosol dispersion along the X, Y, and Z axes during the sneezing event for the first individual, highlighting their dispersion trajectory over time.

Figure 5.21-(a) illustrates that most aerosols expelled along the X axis remain within the 15.9 m to 16.3 m range (indicating a transmission distance of approximately 0.4 m), demonstrating a limited horizontal spread. This indicates that under AC, the sneezing event leads to a forward motion with restricted lateral dispersion.

Figure 5.21-(b) shows that the lateral diffusion of particles along the Y axis ranges from 12.25 to 13.75 m (indicating a transmission distance of approximately 1.5 m), suggesting that airflow induces moderate edgeways spread. The AC system influences this lateral movement, but the particles remain relatively confined within the immediate breathing zone of the infected individual.

Figure 5.21-(c) shows the vertical particle distribution along the Z axis, where the vertical dispersion pattern shows most aerosols remain between 1.2 m and 2.4

m (indicating a transmission distance of approximately 1.2 m), aligning with the typical seated breathing height of the occupants. This reinforces the potential for exposure among individuals placed near the infected individual.



(a) X direction (b) Y direction (c) Z direction

Figure 5.21: Aerosol dispersion through sneezing in X, Y,and Z directions for the first individual during AC.

Figure 5.22 presents the spatial distribution of aerosols expelled from the second infected individual. The particles initially travel in a concentrated forward motion before dispersing as a result of the interaction with indoor airflow. Unlike the first infected individual, where the particles spread rapidly toward the door due to strong airflow ventilation, the dispersion of the second infected individual is more contained within the zone due to their location farther from the AC unit.

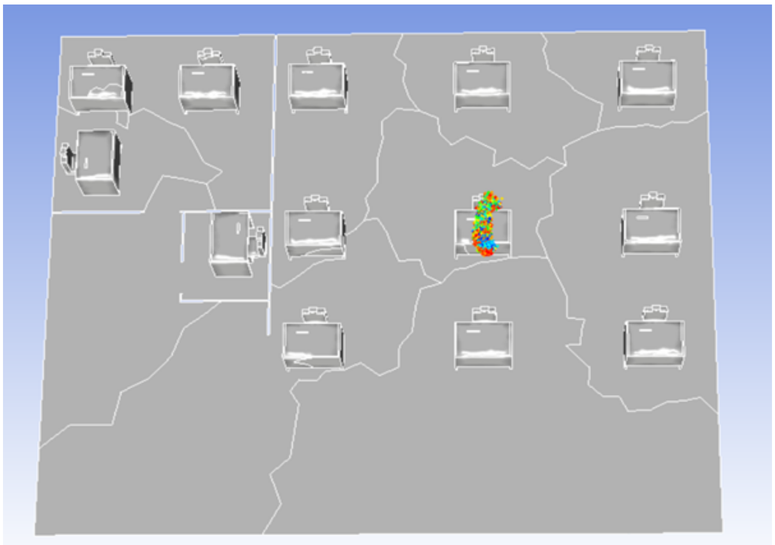


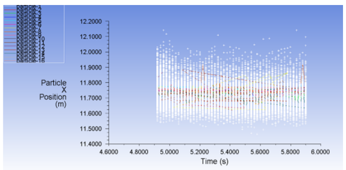
Figure 5.22: Particle transmission from the second infected individual during sneezing.

Figure 5.23 illustrates the aerosol dispersion along the X, Y, and Z axes during the sneezing event for the second individual, highlighting their dispersion trajectory over time.

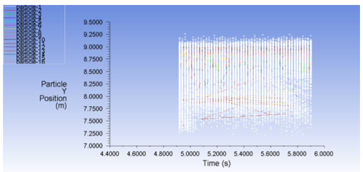
Figure 5.23-(a) illustrates that most aerosols expelled along the X axis remain within the 11.6 m to 11.9 m range (indicating a transmission distance of approximately 0.3 m), showing a relatively restricted lateral spread. The air flow influences the horizontal motion of the particles, preventing excessive dispersion beyond this localised range.

Figure 5.23-(b) shows that the lateral diffusion of particles along the Y axis ranges from 7.5 to 9 m (indicating a transmission distance of approximately 1.5 m), indicating that airflow facilitates a greater spread in this direction compared to the X axis. This suggests that the surrounding airflow plays a role in extending the reach of aerosols beyond the immediate sneezing region.

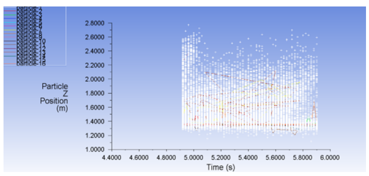
Figure 5.23-(c) shows the vertical particle distribution along the Z axis, where the vertical dispersion pattern indicates that most aerosols remain between 1.3 and 2.1 m (indicating a transmission distance of approximately 0.8 m), aligning with the typical seated breathing height of the occupants. This reinforces the potential exposure risk for people sitting in close proximity to the infected person because the particles remain within the breathing zone for extended periods.



(a) X direction



(b) Y direction



(c) Z direction

Figure 5.23: Aerosol dispersion through sneezing in X, Y,and Z directions for the second individual during AC.

Figure 5.24 illustrates the overall spatial distribution of aerosols expelled by the third infected individual. The results indicate that the particles remain relatively concentrated around the source due to the location of the individual, which was far from the direct airflow pathways generated by the AC. Most of the particles disperse locally, with some lateral spread occurring due to weak indoor air currents.

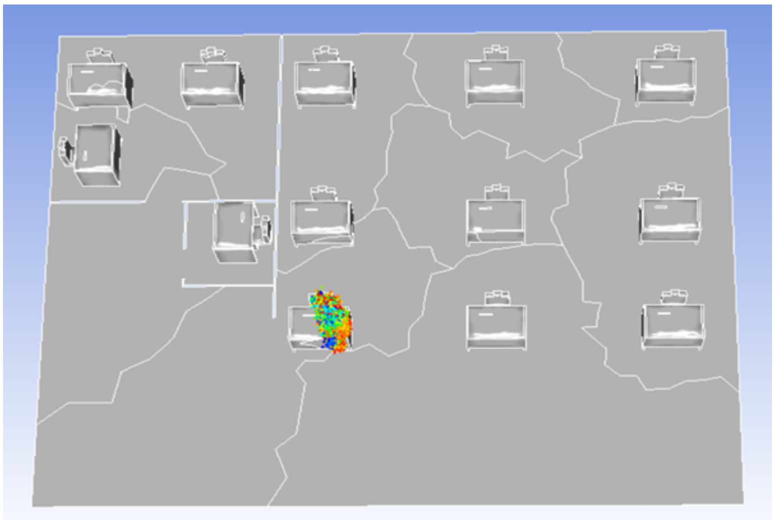


Figure 5.24: Particle transmission from the third infected individual during sneezing..

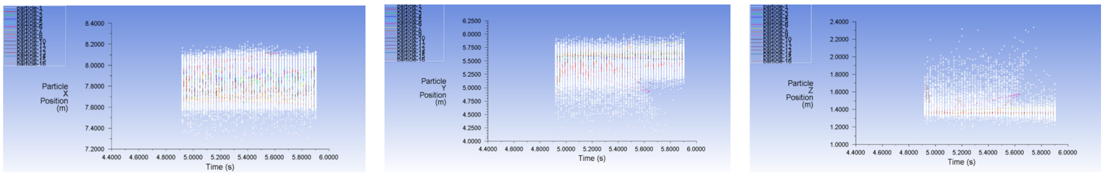
Figure 5.25 illustrates the aerosol dispersion along the X, Y, and Z axes during the sneezing event for the third individual, highlighting their dispersion trajectory over time.

Figure 5.25-(a) illustrates that most aerosols expelled along the X axis remain within the range of 7.6 to 8.1 m (indicating a transmission distance of approximately 0.5 m), demonstrating a limited horizontal spread. The initial high coughing velocity propels the aerosols forward, but their dispersion is largely constrained by the AC effects.

Figure 5.25-(b) shows that the lateral diffusion of particles along the Y axis ranges between 5 and 6 m (indicating a transmission distance of approximately 1 m), indicating moderate side-to-side dispersion. The airflow from the AC system

plays a crucial role in particle transport, with some particles showing a slight deviation due to turbulence.

Figure 5.25-(c) shows the vertical particle distribution along the Z axis, where the vertical dispersion pattern indicates that most aerosols remain between 1.3 and 1.7 m (indicating a transmission distance of approximately 0.4 m), aligning with the typical breathing height of the seated occupants. This suggests a significant potential for transmission to individuals in close proximity to the infected person, particularly those within the immediate vicinity.



(a) X direction (b) Y direction (c) Z direction

Figure 5.25: Aerosol dispersion through sneezing in X, Y,and Z directions for the third individual during AC.

Figure 5.26 illustrates the spatial distribution of particles expelled by the position of the fourth individual. The results show that sneezing leads to a localised dispersion of aerosols with minimal spread beyond the immediate surroundings. The regulation of airflow from the AC system in Zone 2 appears to limit the extent of aerosol movement, containing the majority of particles near the infected individual.

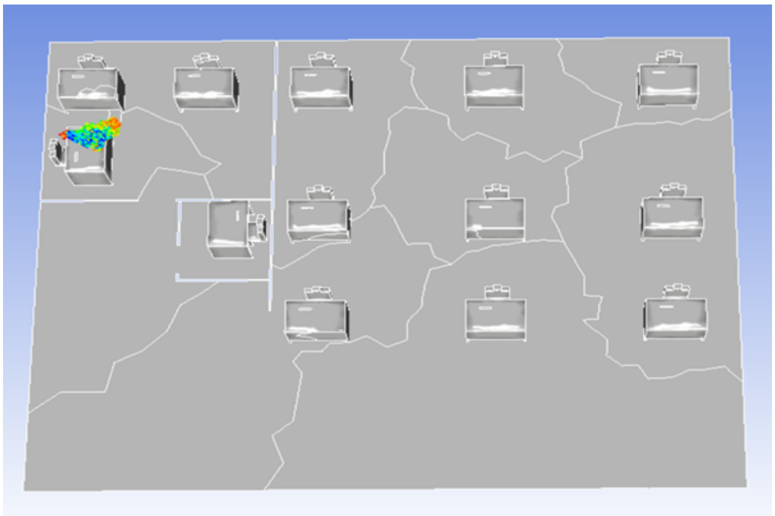


Figure 5.26: Particle transmission from the fourth infected individual during sneezing.

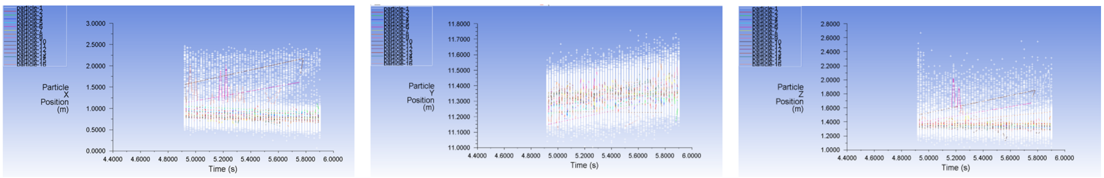
Figure 5.27 illustrates the aerosol dispersion along the X, Y, and Z axes during the sneezing event for the fourth individual, highlighting their dispersion trajectory over time.

Figure 5.27-(a) illustrates that most aerosols expelled along the X axis remain confined within the 0.5 to 2.5 m range (indicating a transmission distance of approximately 2 m). The particles exhibit limited forward movement, primarily influenced by the coughing velocity and the airflow pattern induced by the AC.

Figure 5.27-(b) shows that the lateral spread of aerosols along the Y axis occurs within the range of 11.1 to 11.6 m (indicating a transmission distance of approximately 0.5 m). This relatively constrained dispersion suggests that the AC flow directs the particles within a controlled region, reducing the likelihood of significant lateral spread.

Figure 5.27-(c) shows the vertical particle distribution along the Z axis, where the vertical distribution analysis reveals that most aerosols remain within the range of 1.1 to 2 m (indicating a transmission distance of approximately 0.9 m). This

aligns with the typical breathing zones of the seated occupants, emphasising the potential exposure risk for individuals in close proximity.



(a) X direction (b) Y direction (c) Z direction

Figure 5.27: Aerosol dispersion through sneezing in X, Y,and Z directions for the fourth individual during AC.

5.7 Discussion

This section critically examines the performance of AC in relation to TC and IAQ, with reference to key regulatory standards, including ASHRAE Standard 55, EN 16798, and ISO 7730. This discussion evaluates the temperature distribution, RH, air velocity, and airflow uniformity, identifying areas of compliance and opportunities for optimisation.

5.7.1 Comparison with ASHRAE Standards, EN 16798, and ISO 7730 standards

The effectiveness of AC was assessed against ASHRAE 55, EN 16798, and ISO 7730 for TC. These standards establish acceptable ranges for temperature, humidity, air velocity, and TC indices (PMV and PPD) to ensure that indoor environments support occupant well-being.

According to ASHRAE 55, an acceptable indoor temperature should range between 22 °C and 26 °C, with RH maintained between 30% and 60% to optimise both comfort and air quality. The AC system demonstrated generally stable thermal conditions, with key findings as follows:

- The temperature distribution remained within 22 °C to 25 °C in most of the occupied zones, ensuring compliance with the Category B TC thresholds of ASHRAE 55 and ISO 7730.
- The levels of RH fluctuated between 53% and 70%, exceeding the recommended upper limit of ASHRAE 60% in certain zones, which can contribute to thermal discomfort and increased stability of the airborne virus.

Although AC effectively regulated indoor temperature, excessive humidity remains a concern. This requires dehumidification measures to ensure compliance with the comfort guidelines of ASHRAE 55 and ISO 7730.

Consistent and well-distributed airflow is essential to maintain occupant comfort and prevent stagnant air pockets. ASHRAE 55 recommends an indoor airflow velocity between 0.1 and 0.25 m/s to promote proper air mixing and ventilation effectiveness. The findings revealed significant spatial variations:

- Most of the occupied areas achieved airflow velocity within the recommended range (0.15 m/s to 0.25 m/s), ensuring adequate ventilation and TC.
- Air stagnation (< 0.1 m/s) was detected in specific areas, particularly near corners and non-ventilated sections, leading to localised reductions in air mixing efficiency.

These findings highlight the need for strategic adjustments to the airflow distribution, particularly in areas where stagnant air could lead to CO2 accumulation and thermal discomfort.

ASHRAE 55, EN 16798, and ISO 7730 classify TC using the PMV and PPD indices:

- ASHRAE 55 targets 80% occupancy satisfaction, corresponding to PMV between -0.5 and +0.5 and PPD below 20%.
- Category A (ISO)/I (EN): PMV within ±0.2 and PPD < 6% (high expectations)
- Category B (ISO)/II (EN): PMV within ±0.5 and PPD < 10% (normal expectations)
- Category C (ISO)/III (EN): PMV within ±0.7 and PPD < 15% (moderate comfort)

The AC system largely met the ASHRAE and ISO standards for TC, with PMV values ranging from -0.3 to +0.5 in most areas, ensuring compliance with Category B comfort levels. However, localised temperature variations near the lower limit (22 °C) in some areas led to PPD values reaching 10% to 15%, indicating potential discomfort among a portion of the inhabitants.

5.7.2 Identification of Air Conditioning Dead Zones

AC dead zones, characterised by low air velocity (< 0.05 m/s) and minimal air exchange, were identified in multiple locations within the office environment. These stagnant zones were predominantly observed in corners and areas far from air supply vents, resulting in insufficient fresh air circulation. The formation of dead zones poses a significant challenge to IAQ and occupant well-being because these areas facilitate the accumulation of pollutants, the accumulation of CO2, and the localised thermal discomfort.

CFD simulations revealed that restricted airflow zones exhibited slightly elevated temperatures (24 °C–25 °C) and increased RH levels (>65%), both of which contribute to a decrease in TC. This trend aligns with previous research, which indicates that areas with poor air movement often experience uneven temperature distribution, moisture retention, and reduced air quality. To mitigate dead zones, strategies such as adjusting diffuser placement, increasing air circulation, and implementing demand-controlled ventilation (DCV) should be considered.

5.7.3 Impact of Air Velocity on Virus Dispersion

The dispersion and persistence of virus-laden aerosols are significantly influenced by air velocity. CFD simulations indicate that higher air velocities (> 0.25 m/s) facilitate faster aerosol transport, effectively reducing localised virus concentrations by accelerating particle dilution and removal. However, this increased momentum extends the travel distance of airborne particles, potentially exposing occupants over a broader area.

In contrast, low-speed areas (< 0.1 m/s) exhibited prolonged aerosol suspension, increasing the risk of extended exposure to the occupants. In such regions, where air circulation is not sufficient to effectively dilute contaminants, viral particles linger for extended periods, increasing the probability of inhalation by individuals in close proximity.

5.7.4 Impact of Relative Humidity on Comfort and Airborne Virus Stability

RH plays a fundamental role in both TC and airborne pathogen stability. The CFD analysis revealed RH levels that fluctuated between 53% and 70%, with localised regions exceeding 65%, particularly in areas with low air circulation. ASHRAE Standard 55 recommends maintaining the RH within 30% to 60% to optimise the comfort of the occupant and minimise health risks.

Excess humidity (> 60%) negatively affects indoor comfort by reducing the efficiency of evaporative cooling, making the environment feel warmer and more crowded than the actual temperature suggests. In addition, elevated RH contributes to increased microbial growth, mould formation, and greater stability of airborne viruses. High humidity levels allow virus-laden aerosols to retain moisture for longer periods, prolonging their suspension time in the air and increasing the likelihood of cross-contamination between occupants.

The findings indicate that AC alone does not effectively regulate RH, especially in areas with poor air mixing. Areas with stagnant airflow exhibited higher RH levels (> 65%), which exacerbates thermal discomfort and potentially increasing virus survival rates. This highlights the need for integrated humidity management strategies, such as incorporating dehumidification measures or ventilation adjustments.

5.7.5 Scenario Performance Evaluation

The AC system's performance was assessed based on multiple parameters, including air velocity, temperature, RH, PMV, and PPD. Although AC improved overall airflow, it failed to achieve uniform distribution, leading to localised comfort problems and suboptimal air mixing. The system effectively controlled temperature but faced challenges in humidity regulation and airflow uniformity. Addressing stagnant air pockets and optimising RH control would improve overall IAQ, TC, and infection risk mitigation.

Table 5.4 summarises the overall performance of the AC system.

Case	**Air Velocity**	**Temperature**	**RH**	**PMV**	**PPD**
Baseline Case Study	0.05–0.25 m/s	22–25 °C	53–70%	0.2 to 1.5	10–40%

Table 5.4: Summary of AC performance

5.8 Recommendations for Optimising AC Performance

A number of optimisations should be considered to enhance the effectiveness of AC and maintain IAQ and TC. One of the primary concerns identified in this study was the presence of stagnation of airflow and dead zones, leading to localised discomfort and accumulation of pollutants. To mitigate these issues, the air distribution should be optimised through improved diffuser placement and airflow direction adjustments. To minimise stagnation and promote uniform air mixing throughout the space, the supply vents should be strategically positioned and return air outlets should be designed. In addition, the use of adjustable airflow diffusers can help to regulate air velocity and ensure that the occupants do not experience discomfort due to excessive cooling or draughts.

Another key improvement involves increasing the intake of fresh outdoor air. The current AC system primarily recirculates indoor air, which can lead to the accumulation of CO2, pollutants, and airborne pathogens. Implementing DCV with CO2 and humidity sensors can optimise outdoor air exchange rates, ensuring sufficient dilution of indoor contaminants while maintaining energy efficiency. Furthermore, incorporating HEPA or MERV-rated filtration systems can significantly reduce the concentration of airborne particles, thus improving IAQ and minimising the risk of airborne virus transmission.

Humidity control must also be addressed to align with the ASHRAE recommendations. This study found that RH levels in AC ventilated spaces occasionally exceeded 65%, which increases the risk of microbial growth and virus persistence. To prevent this, it is recommended to integrate dehumidification systems into the ventilation network. Furthermore, maintaining RH levels within the recommended range of ASHRAE (i.e., 30% to 60%) can be achieved by adjusting ventilation rates based on humidity levels in real time, ensuring that excess moisture does not accumulate in the indoor environment.

Finally, implementing PV solutions, such as desk-mounted ventilation units or localised airflow adjustments, could improve occupant comfort while reducing the total energy demand of the system. Smart ventilation systems, which are equipped with real-time monitoring and automated airflow adjustments, can further enhance AC performance by dynamically adapting to occupancy levels and environmental conditions.

5.9 Conclusion

This chapter has critically evaluated the effectiveness of AC, specifically the four-way ceiling cassette system, in regulating airflow distribution, TC, RH, IAQ, and airborne infection risk in an open-plan office environment. Using CFD simulations, the findings provide a detailed assessment of the strengths and limitations of this ventilation system, particularly in meeting ASHRAE TC and IAQ standards.

The validation process demonstrates a high degree of accuracy between the CFD model and real sensor data, confirming the reliability of the simulation framework. However, the airflow analysis has highlighted significant limitations, particularly the presence of stagnant airflow zones (dead zones) at corners and areas far from air supply outlets. These regions exhibited low-velocity air circulation ($<$0.1 m/s), leading to potential accumulation of contaminants and thermal discomfort. To address this problem, modifications such as repositioning air diffusers, increasing air exchange rates, or incorporating hybrid ventilation strategies (AC + natural ventilation) should be considered.

The regulation of temperature remained within acceptable comfort limits (22 °C to 25 °C), yet spatial variations indicate that AC alone does not ensure a uniform temperature distribution across the office. Similarly, RH levels fluctuated between

53% and 65%, exceeding the recommended upper limit of ASHRAE 60% in some areas. This is particularly concerning because elevated levels of RH can enhance viral stability, increasing the risk of airborne transmission. These results highlight the need for additional humidity control measures, such as dehumidification or integrating fresh air intake to balance moisture levels.

The PMV and PPD analysis provided insight into occupant TC, showing that while some zones maintained near-neutral thermal conditions (0.2 to 1.8 PMV), others experienced discomfort due to inconsistent airflow patterns. In particular, Zone 3 exhibited the highest thermal dissatisfaction, with PMV values reaching 2.2 and PPD values exceeding 40%, indicating thermal discomfort in areas with reduced air circulation and heat buildup. These findings suggest that modifying air distribution strategies and improving localised heating efficiency could improve TC in those areas that are currently underperforming.

A critical limitation of this AC system is that it does not introduce fresh air but instead recirculates indoor air. This air recirculation process can inadvertently transport pollutants, viral aerosols, and contaminants throughout the office, reintroducing previously expelled particles into the ventilation unit and redistributing them. Consequently, areas with limited airflow may experience increased airborne infection risks, particularly in the presence of an infected individual. To mitigate this problem, HEPA or MERV-rated filters should be incorporated into the ventilation system to capture airborne contaminants before recirculation. Furthermore, integrating fresh air intake through hybrid ventilation approaches could dilute indoor pollutant concentrations, improving overall IAQ.

Aerosol dispersion analysis highlights the role of air velocity in the influence of particle transport. High-velocity airflow (>0.25 m/s) contributes to wider aerosol dispersion, potentially increasing the spread of infectious particles across the zone. In contrast, low-velocity airflow (<0.1 m/s) allows suspended particles to linger, increasing the risk of localised airborne transmission. These findings underscore the importance of balanced airflow control to prevent excessive spread while ensuring efficient removal of contaminants.

Compared to ASHRAE Standard 55 for TC and ASHRAE Standard 62.1 for IAQ, the results indicate partial compliance, with temperature control and central airflow efficiency meeting requirements. However, humidity control issues, air recirculation, and nonuniform ventilation distribution present significant challenges. This reinforces the need for strategic modifications to ensure optimal ventilation performance.

This study is able to propose several recommendations to improve AC efficiency:

- Optimising air distribution: Adjusting the placement of the air diffuser and the direction of the supply air could reduce stagnant airflow zones and improve uniform air mixing.
- Enhancing IAQ through fresh air intake: Integrating natural ventilation strategies, such as controlled window openings, DCV, or hybrid systems, could dilute indoor pollutants and improve air freshness.
- Humidity control measures: Maintaining RH between 30% and 60% through dehumidification and hybrid ventilation solutions could prevent excessive moisture buildup, which influences viral stability.
- Improved filtration systems: Upgrading AC filters to HEPA or MERV-rated standards would enhance aerosol removal efficiency, reducing airborne virus transmission risks.
- Increased air exchange rates: Enhancing ventilation rates beyond 4 ACH would help mitigate pollutant recirculation and improve IAQ.

This chapter contributes to the thesis by offering a validated CFD-based analysis of a commonly used AC system, highlighting its impact on airflow, temperature distribution, RH control, and airborne virus transmission. It introduces

PMV and PPD mapping to assess spatial variations in occupant thermal comfort and identifies key system shortcomings, such as dead zones and recirculated air contamination. These insights establish a quantitative baseline for evaluating alternative ventilation strategies in subsequent chapters and provide practical recommendations for enhancing AC-driven IAQ and infection control.

In conclusion, this study highlights the performance limitations of AC in achieving optimal IAQ and TC. Although the four-way ceiling cassette system effectively regulates temperature and airflow in central zones, it does not eliminate dead zones, control RH levels, or prevent pollutant recirculation. **In direct response to Research Question 3 (RQ3)**, the findings demonstrate that relying solely on recirculating AC systems is insufficient to minimise the risk of airborne infections. This is primarily due to inadequate fresh air supply, uneven airflow distribution, and the recirculation of potentially contaminated air. Therefore, to reduce infection risk and enhance ventilation performance, a holistic approach is required that incorporates enhanced filtration, strategic airflow modifications, and fresh air integration. It is recommended that future research should investigate long-term ventilation strategies under varied seasonal conditions and occupancy levels, which would provide additional insight into the most effective AC configurations in office environments.

Chapter 6

Natural Ventilation

6.1 Introduction

6.1.1 Background and Importance of Natural Ventilation

This chapter directly addresses **Research Question 3 (RQ3) and Research Question 4 (RQ4)**. Building upon the findings of Chapters 4 and 5, which highlighted the limitations of the existing air conditioning (AC) system—particularly its reliance on air recirculation and inability to maintain consistent airflow or thermal conditions—this chapter investigates natural ventilation as a passive alternative. It evaluates its performance in regulating airflow, maintaining thermal comfort, and mitigating airborne infection risks in the same office environment. Using CFD simulations, the chapter analyses various natural ventilation scenarios under different environmental conditions to assess their effectiveness in enhancing indoor air quality (IAQ), pollutant dilution, and thermal stability.

Natural ventilation (NV) is a fundamental strategy in the energy-efficient design of buildings, utilising airflows driven by natural forces such as buoyancy and wind pressure, thus eliminating the need for mechanical energy consumption [309]. Due to its operational simplicity and lower capital investment, NV is widely adopted in educational buildings, particularly classrooms, across various regions [310]. In temperate climates, NV is typically used during transitional seasons, such as spring and fall, whereas in tropical regions it can be used throughout the year.

In university buildings, NV is predominantly facilitated through operable openings, such as doors and windows, providing a passive and energy-free means of regulating indoor air quality and thermal conditions. Manual adjustment of these openings by the occupants to achieve TC is often considered to be an adaptive behavioural response [311].

The efficiency of NV is influenced by several interdependent factors, including external climatic conditions, the architectural configuration of the openings of the building, occupant behaviour, and internal heat and pollutant sources. Seasonal variations, fluctuations in ambient temperature, wind speed, and humidity levels affect the performance of NV systems. In the colder months, low outdoor temperatures can limit the feasibility of prolonged window openings, potentially compromising TC. In contrast, in warmer climates, inadequate NV management may result in overheating, reducing occupant comfort [312]. Consequently, optimising NV strategies requires a careful balance between environmental variables, building design considerations, and user interactions to maximise ventilation effectiveness while ensuring indoor TC.

6.1.2 The Role of Natural Ventilation in Enhancing Indoor Air Quality and Thermal Comfort, and Mitigating Infection Risk

The capacity of NV to improve IAQ and TC has been widely recognised in architectural and environmental research [172, 210, 313]. Optimising NV systems requires the integration of strategic elements of building design, including appropriately placed windows, doors, solar chimneys, and wind capture devices, all of which help to facilitate air movement and regulate indoor temperatures [314–318].

Beyond its role in thermal regulation, NV has been identified as an effective strategy for infection control, particularly in mitigating the spread of airborne respiratory diseases [319]. The COVID-19 pandemic has underscored the critical importance of adequate ventilation in reducing viral transmission. Empirical studies indicate that well-ventilated spaces, which are characterised by adequate airflow and high dilution rates, significantly decrease aerosol concentrations, thus limiting the airborne virus transmission such as SARS-CoV-2 [170, 172, 320]. Well-designed NV systems can substantially reduce indoor pollutant concentrations and mitigate airborne virus transmission [321].

Despite its benefits, NV also poses challenges related to the dispersion of contaminants within indoor environments. Research has highlighted the bidirectional transmission of airborne viruses between indoor and outdoor spaces, particularly when unfiltered outdoor air is introduced through NV openings [322, 323]. In addition, inconsistent airflow patterns can result in stagnant air zones, where pollutants may accumulate and persist for extended periods [321, 324]. Addressing these issues requires careful airflow planning, strategic window placement, and optimised opening configurations to maximise ventilation effectiveness while minimising health risks.

Another significant challenge associated with NV is the variability in ventilation rates due to fluctuating wind speeds and directions, which can compromise indoor thermal stability [325]. Excess ventilation in winter may lead to over-cooling, while insufficient airflow during summer can exacerbate indoor overheating and humidity accumulation, which can negatively impact occupant comfort. Therefore, achieving an optimal balance between ventilation effectiveness and thermal stability requires an understanding of airflow dynamics and environmental conditions.

To address these issues, various wind-driven NV strategies have been explored in architectural research, each offering distinct advantages depending on the design of the building and the climatic conditions, including single-sided ventilation

(SSV), cross-ventilation (CV), wind-catcher ventilation (WCV), wing-wall ventilation, wind-scoop ventilation, turbine ventilators, and roof vents [314, 326]. The effectiveness of each approach varies, based on factors such as wind availability, building orientation, and the specific ventilation requirements of the indoor space.

6.1.3 Cross-ventilation as an Effective Natural Ventilation Strategy

Among the various NV strategies, CV is particularly effective in enhancing air movement and reducing indoor pollutant concentrations. CV operates by utilising pressure differentials between the windward and leeward facades of a building, which allows fresh air to enter from one side while facilitating the exit of stale air through the opposite side [327]. This pressure-driven process significantly improves air exchange rates, making CV more effective in improving IAQ than SSV [328].

Despite its advantages, CV remains underutilised in urban buildings due to architectural restrictions, such as partitioned floor plans and enclosed interior spaces, which obstruct the creation of direct airflow pathways [329]. Unlike more open architectural layouts, where cross-ventilation can function efficiently, many urban buildings are designed with rooms that are separated across different facades, which limits the feasibility of direct air circulation [328, 329]. However, emerging design strategies, including adjustable partitions, optimised door gaps, and strategically placed windows, can improve CV performance, which makes it a viable alternative for office and classroom environments.

The effectiveness of CV in mitigating airborne pollutants and improving IAQ has been the subject of numerous experimental and numerical studies. Irga and Torpy [330] conducted an empirical investigation comparing the efficacy of three ventilation systems: CV, mechanical ventilation (MV), and a hybrid ventilation mode in various office environments. Their results demonstrate that the average concentration of airborne contaminants (COC) was significantly lower under CV than under MV or hybrid systems. Similarly, Abbas and Dino [331] employed numerical simulations to assess the influence of different CV design parameters, such as the window-to-wall ratio (WWR) and opening configurations, on the dispersion of airborne particles in a 1024 m^3 office space. Their findings reveal that increasing WWR has a substantial impact on the reduction of contaminants, suggesting that WWR adjustments may be a more effective mitigation strategy than altering the placement of openings.

Further studies have examined the role of CV in classrooms, particularly in reducing the risk of airborne virus transmission. Ren et al. [297] conducted numerical simulations to evaluate the effects of different window opening configurations on the distribution of airborne contaminants in a classroom setting. Their results indicate that when an infected occupant was positioned near the CV inlets, a notable disparity in contaminant concentrations was observed between different sections of the classroom, which highlights the influence of the occupant position on CV performance. Park [172] conducted a numerical assessment that compared the infection risk posed by an infected student in a 168 m^3 classroom under SSV and CV conditions. Park explored multiple window opening ratios (15%, 30%, and 100%) and found that after a three-hour exposure period the infection risk under CV was approximately 2.5 and 3.3 times lower than under SSV for window opening ratios of 15% and 30%, respectively.

6.1.4 Chapter Objectives

The primary objective of this chapter is to evaluate the performance of NV in maintaining optimal airflow patterns, TC, and control of airborne infections in an office environment. This study aims to evaluate the effectiveness of NV strategies using CFD simulations. Specifically, this chapter seeks to:

- Analyse the airflow distribution in different NV scenarios and its impact on air circulation.
- Evaluate the variations in temperature and RH in NV strategies.
- Assess occupant TC using the PMV and PPD indices.
- Examine aerosol dispersion patterns during coughing and sneezing events to understand the risk of airborne virus transmission.
- Compare NV performance with the standards of ASHRAE 55, EN 16798, and ISO 7730 for TC to ensure that the system meets the recommended ventilation effectiveness criteria.
- Identify the most effective NV strategy that improves IAQ and reduces thermal discomfort.

6.2 Methodology

This study used a CFD simulation approach to assess the performance of NV in an open-plan office environment. This methodology follows a structured framework, beginning with the identification of key parameters and solver settings, which is followed by the development of a computational model that incorporates geometry, meshing, and boundary conditions. The CFD simulation evaluates IAQ, TC, and aerosol dispersion, providing insights into the effectiveness of NV strategies under different seasonal conditions. The results are analysed for airflow patterns, temperature regulation, RH, TC indices of the occupants (PMV and PPD), and risks of transmission of airborne viruses. Finally, recommendations are derived based on the findings to optimise NV performance.

The general research framework is illustrated in Figure 6.1, which summarises the step-by-step process undertaken in the simulations.

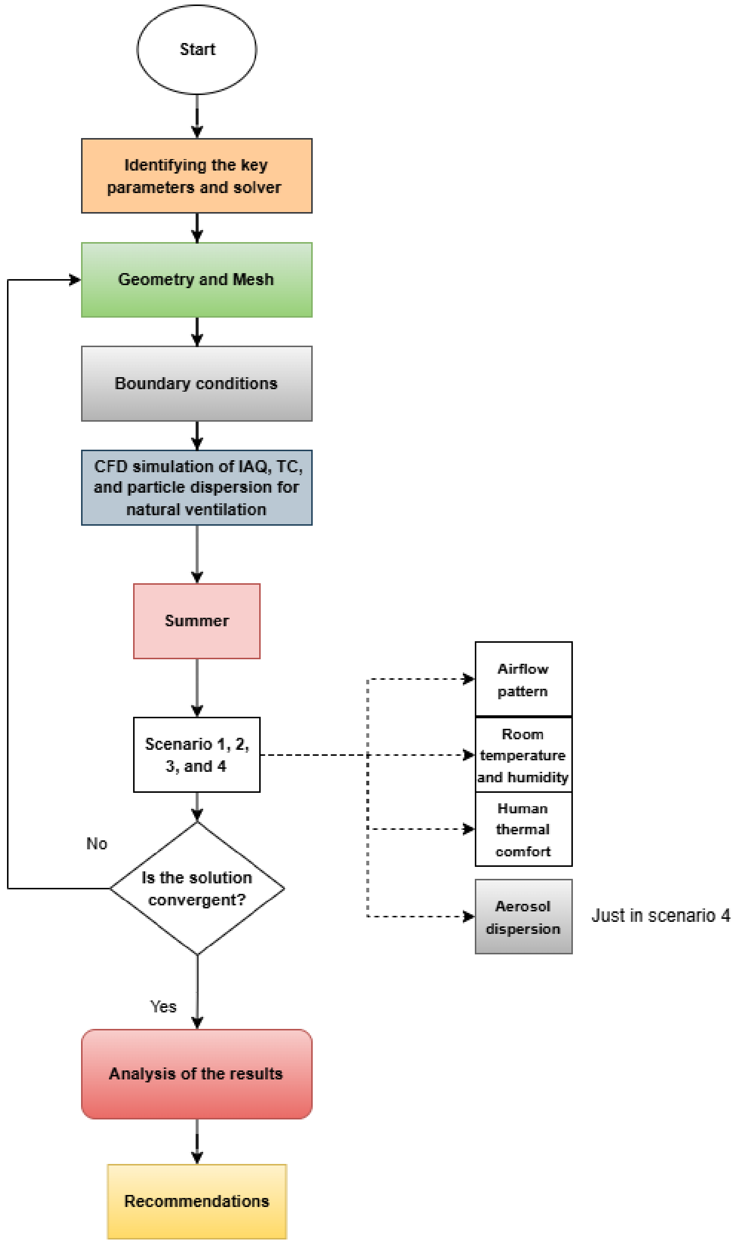


Figure 6.1: Overview of the methodology for NV simulations

6.3 Scenario Development

This chapter evaluates five different NV scenarios to evaluate system performance under different seasonal conditions and ventilation strategies, as summarised in

Table 6.1. Each scenario evaluates airflow distribution, temperature control, humidity levels, and human TC metrics.

Scenario No.	Season	Ventilation Configuration	Environmental Conditions
1	Summer	Single Window Open (Window 4)	T = 19°C, V = 1.9 m/s, RH = 0.0083
2	Summer	Single Window Open (Window 4)	T = 19°C, V = 1.9 m/s, RH = 0.009
3	Summer	Single Window Open (Window 4)	T = 19°C, V = 3.0 m/s, RH = 0.0083
4	Early Summer	Three Windows Open (Window 1,Window 6,Window 9)	T = 17.5°C, V = 3.0 m/s, RH = 0.0115

Table 6.1: NV scenarios and their environmental conditions.

6.4 Boundary Conditions

NV scenarios were simulated for summer conditions because opening windows during winter could cause thermal discomfort to the occupants. The boundary conditions were carefully designed to capture realistic airflow dynamics, thermal behaviour, and respiratory particle dispersion in the teaching office environment in various NV settings. These conditions account for wind-driven airflow, buoyancy effects, and CV efficiency, ensuring a comprehensive assessment of indoor air quality and TC in naturally ventilated spaces.

The air flow entering the office was modelled as a velocity-inlet boundary condition, simulating fresh outdoor air entering through open windows. Inlet velocity varied in different scenarios, reflecting changing wind conditions and ventilation strategies. The air temperature at the input was set to 19 °C and 17.5 °C, depending on the external climate variations. This ensures the simulation accurately captured temperature-driven buoyancy forces and their influence on indoor airflow patterns.

The air outlet was defined as a pressure outlet with a static pressure condition of zero, allowing for unrestricted airflow discharge through open doors or designated ventilation openings. This configuration facilitated continuous air exchange, which ensures the removal of stale indoor air while preventing the build-up of unphysical pressure within the domain. The combination of natural inlets and outlets replicated a passive airflow system, accurately modelling real-world wind-driven ventilation conditions in an office setting.

Each NV scenario was designed to evaluate the air velocity distribution, the efficiency of CV, and the impacts on TC in the three office zones. In Scenario 1, outdoor air entered through Window 4 at a velocity of 1.9 m/s with a humidity level of 0.0083 and the inlet air temperature was set at 19 °C to represent realistic summer conditions. Scenario 2 maintained the same setup as Scenario 1 but the humidity level was adjusted to 0.009, which captures the impact of slight humidity variations on NV efficiency. In Scenario 3, the inlet velocity was increased to 3.0 m/s, with the humidity level set to 0.0083, which allows an analysis of how higher wind speeds influence indoor air circulation. Scenario 4 introduced multiple openings by activating Window 1, Window 9, and Window 17, with an inlet velocity of 3.0 m/s and a humidity level of 0.0115. This setup was designed to evaluate the effectiveness of CV, demonstrating how multiple openings improve airflow distribution and improve contaminant dilution efficiency compared to single-window configurations.

A summary of key boundary conditions is presented in Table 6.3, which details the temperature, velocity, and pressure conditions assigned to different surfaces, airflow sources, and respiratory events. These boundary conditions were essential to capture the complex thermal and airflow interactions that define naturally ventilated indoor spaces, providing valuable insights into ventilation effectiveness, TC, and airborne contaminant control.

To evaluate the effectiveness of NV in controlling the risks of airborne infection, the 12th simulation case was developed, as described in Table 6.2. Cases 1, 3, 5, and 7 assess airflow, room temperature, and RH and distribution. Cases 2, 4, 6, and 8 evaluate the implications for TC of NV by analysing the thermal perception of the occupant. Cases 9 to 12 introduce an infected individual seated in different positions (A, B, C, and D) to assess aerosol dispersion patterns and infection risks across various spatial configurations. These seating locations were selected to represent typical workstation layouts in an open-plan office, which allows an analysis of how airflow direction, diffuser positioning, and ventilation efficiency influence particle transport and potential exposure risks.

Case No.	**Scenario**	**Infected Source**	**Notes**
1	Scenario 1	None	Assessment of ventilation performance
2	Scenario 1	None	Assessment of thermal comfort
3	Scenario 2	None	Assessment of ventilation performance
4	Scenario 2	None	Assessment of thermal comfort
5	Scenario 3	None	Assessment of ventilation performance
6	Scenario 3	None	Assessment of thermal comfort
7	Scenario 4	None	Assessment of ventilation performance
8	Scenario 4	None	Assessment of thermal comfort
9	Scenario 4	A	Assessment of infection risk
10	Scenario 4	B	Assessment of infection risk
11	Scenario 4	C	Assessment of infection risk
12	Scenario 4	D	Assessment of infection risk

Table 6.2: Overview of simulation cases during the NV.

Boundary Condition	Type	Specification
Air Inlet	Velocity-Inlet	T = 17.5 °C and 19 °C, wind-driven airflow
Air Outlet	Pressure Outlet	Zero static pressure
Walls	No-Slip	T = 15 °C (representing heat exchange)
Occupants (Body)	Thermal Source	T = 24 °C
Occupants (Head)	Thermal Source	T = 34 °C
Occupants (Mouth)	Thermal Source	T = 36 °C
Coughing	Particle Source	V = 11.8 m/s, T = 36 °C
Sneezing	Particle Source	V = 70 m/s, T = 36 °C

Table 6.3: Summary of boundary conditions for NV simulations.

6.5 Results

This section presents the findings of four distinct NV scenarios, each designed to assess NV in regulating IAQ, TC, and airflow distribution. This study specifically examines the influence of outdoor air infiltration through open windows, focussing on key parameters such as air velocity patterns, temperature variations, RH and TC indices, including PMV and PPD.

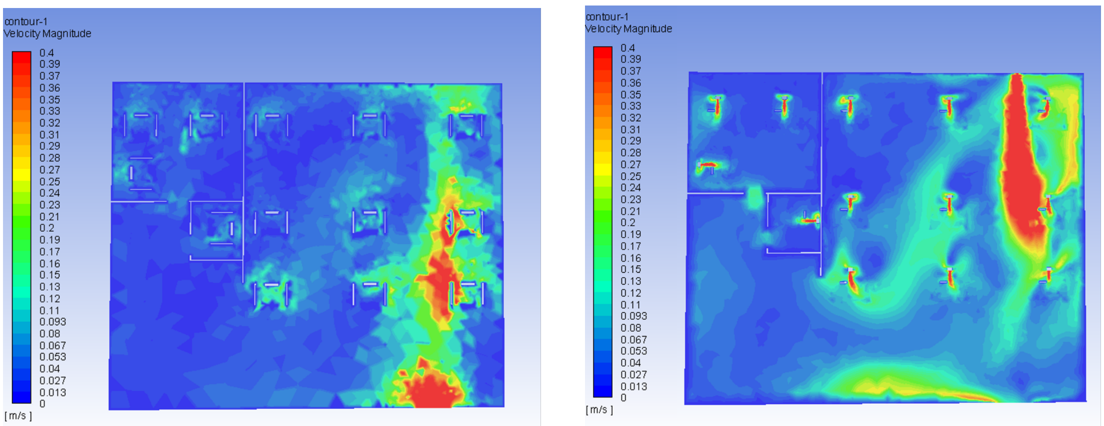
6.5.1 Scenario 1

The air velocity distribution across the three office zones under NV in Scenario 1 provides critical insights into airflow uniformity and the overall efficiency of NV characterised by opening Window 4, with outdoor air entering at a velocity of 1.9 m/s and a humidity level of 0.0083. The inlet air temperature was set to 19°C in Ansys to represent realistic summer conditions.

6.5.1.1 Air Velocity Pattern

Figures 6.2 show the overall distribution of air velocity in all three zones. Most of the office area displays air velocities between 0.06 and 0.08 m/s, with higher velocities concentrated near the open window and the last row of occupants in Zone 1. The remaining areas exhibit low airflow, indicating stagnant zones that require additional ventilation measures to improve circulation.

In general, this scenario reveals that most of the office has low air velocity, leading to several dead zones with limited airflow. These findings highlight the need for additional ventilation measures or mixed-mode ventilation to ensure effective air distribution throughout the office.



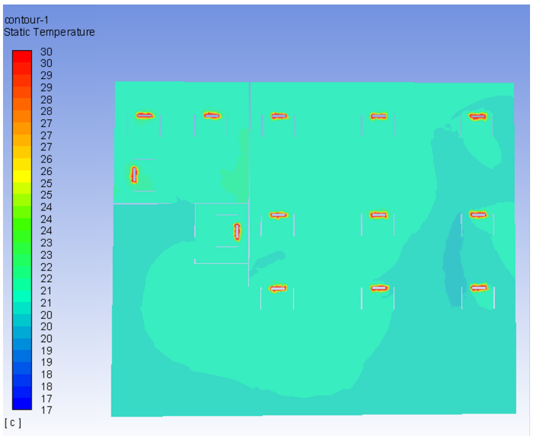
(a) z = 1 m (b) z = 2 m

Figure 6.2: Air velocity contour in z direction during Scenario 1 of NV

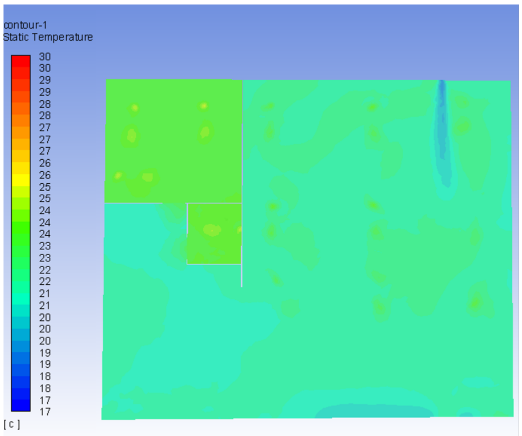
6.5.1.2 Room Temperature and Relative Humidity

The temperature distribution between the three zones within the office space under NV conditions is shown in Figures 6.3. These figures highlight the spatial temperature variations influenced by air inflow from the open window and heat sources such as occupants and equipment.

The large office (Zone 1) benefits from direct inflow of outdoor air, maintaining temperatures between 20 °C and 21 °C in much of the area. However, temperatures near the occupants can reach 23 °C, particularly in regions away from direct airflow. In medium and small offices (zones 2 and 3), temperatures are higher, ranging between 24 °C and 25 °C, suggesting that these areas experience limited airflow, leading to warmer and potentially uncomfortable conditions.



(a) z = 1 m



(b) z = 2 m

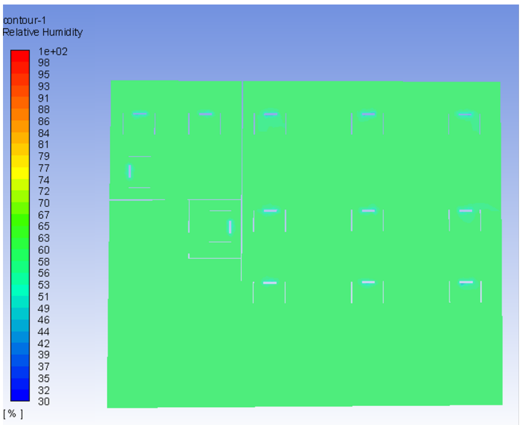
Figure 6.3: Temperature contour in z direction during Scenario 1 of NV

The distribution of RH in the three office zones in Scenario 1 provides insights into moisture regulation and its interaction with air circulation, the presence of the occupant and electronic equipment.

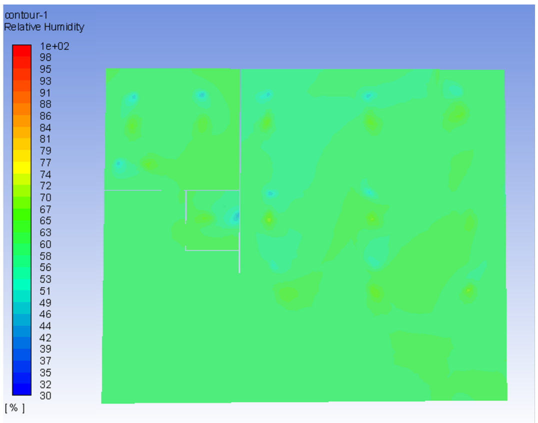
Figure 6.4 presents the combined RH distribution in the three zones. Most areas show RH levels of around 65%, with certain localised regions reaching up to 60%.

These higher humidity concentrations are observed near individuals, electronic equipment, and corners, where airflow may be less effective in dispersing moisture. The elevated RH is consistent with the continuous influx of high-humidity outdoor air, especially in areas where NV dominates.

In general, the findings indicate that while NV can achieve a reasonable air distribution, the high humidity of the incoming outdoor air imposes a challenge in maintaining optimal indoor RH levels.



(a) z = 1 m



(b) z = 2 m

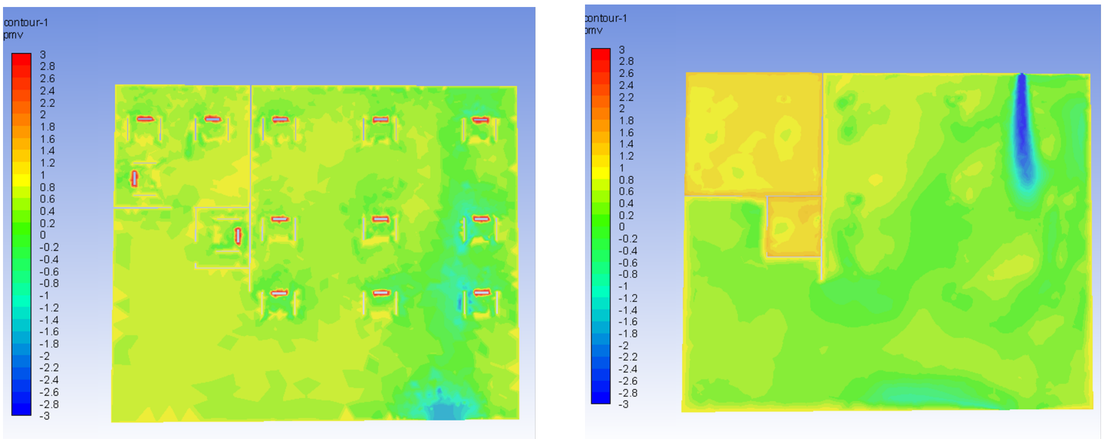
Figure 6.4: RH contour in z direction during Scenario 1 of NV

6.5.1.3 Predicted Mean Vote and Predicted Percentage of Dissatisfied

The distribution of PMV values in the three office zones in Scenario 1 reflects the influence of NV and localised heat sources on TC, as shown in Figures 6.5.

Zone 1 exhibits PMV values ranging from 0 to 0.8, which indicates relatively comfortable conditions with minimal heat discomfort. In contrast, Zones 2 and 3 experience PMV values up to 1.2, indicating that occupants in these zones are likely to feel slightly warm. The observed thermal disparity can be attributed to closed windows and less effective NV in these zones compared to Zone 1.

The spatial variation in PMV values suggests that Zone 1 benefits from better airflow due to the open window, maintaining optimal TC, while Zones 2 and 3 may require additional ventilation improvements to mitigate slightly warm conditions and improve occupant comfort. This result highlights the importance of window placement and airflow optimisation in naturally ventilated office settings.



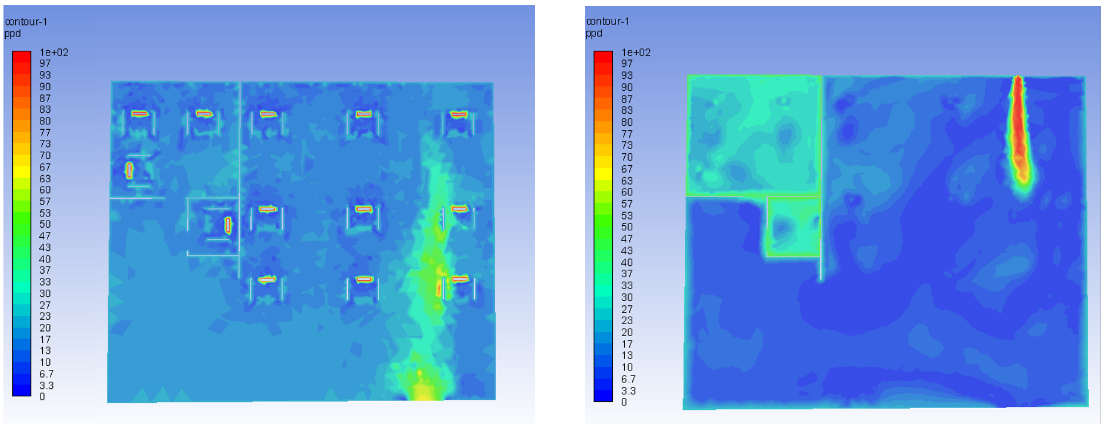
(a) z = 1 m (b) z = 2 m

Figure 6.5: PMV contour in z direction during Scenario 1 of NV

The distribution of PPD corresponds directly to the previously analysed PMV values, highlighting areas where occupants may express discomfort due to variations in thermal conditions and airflow patterns.

Figure 6.6 provides an overall view of the distribution of PPD in the three offices. Zones 2 and 3 exhibit higher PPD values, with levels of dissatisfaction reaching 40% in localised areas, particularly near heat sources or poorly ventilated regions. In contrast, Zone 1 shows better TC, and most areas maintain PPD values below 20%, probably due to the effective NV provided by the open window.

These results suggest that while NV is beneficial in mitigating discomfort in Zone 1, it does not provide uniform comfort throughout the office space. Zones 2 and 3 experience greater dissatisfaction, primarily due to limited direct airflow and localised heat build-up. To address these disparities, the implementation of mixed mode ventilation or the introduction of passive airflow mechanisms, such as additional openings or fans, could help to improve overall comfort and reduce PPD levels to acceptable thresholds. This approach would create a more balanced indoor environment, thus improving occupant satisfaction and productivity.



(a) z = 1 m (b) z = 2 m

Figure 6.6: PPD contour in z direction during Scenario 1 of NV

6.5.2 Scenario 2

The air velocity distribution across the three office zones under NV in Scenario 2 provides critical insights into airflow uniformity and the overall efficiency of NV characterised by opening Window 4, with outdoor air entering at a velocity of 1.9 m/s and a humidity level of 0.009. The inlet air temperature was set to 19 °C in Ansys to represent realistic summer conditions.

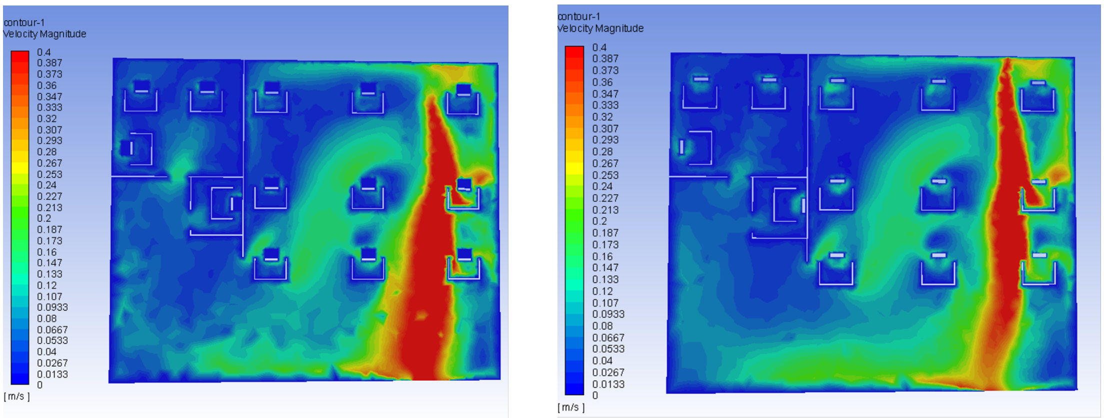
6.5.2.1 Air Velocity Pattern

Figures 6.7 illustrate airflow characteristics in different zones, highlighting areas of effective ventilation, potential stagnation, and deviations from the optimal air distribution. The simulated air velocity within the office space ranged between

0 and 0.4 m/s, with localised airflow patterns that highlight both well-ventilated and stagnant zones.

he results indicate that most of the office exhibits velocities between 0.06 and 0.08 m/s, with higher values located near the open window and the last row of occupants in Zone 1. However, several regions, particularly in Zones 2 and 3, experience low velocities, contributing to stagnant zones with inadequate air exchange.

This scenario reveals that NV through a single open window, although effective in some localised areas, is insufficient to achieve uniform airflow throughout the office. The presence of several dead zones in Zones 2 and 3 highlights the need for additional ventilation solutions, such as mixed-mode ventilation or the strategic placement of additional windows and passive airflow pathways. By addressing these deficiencies, it would be possible to improve indoor air circulation, thereby reducing pollutant accumulation and enhancing overall TC and occupant well-being.



(a) z = 1 m (b) z = 2 m

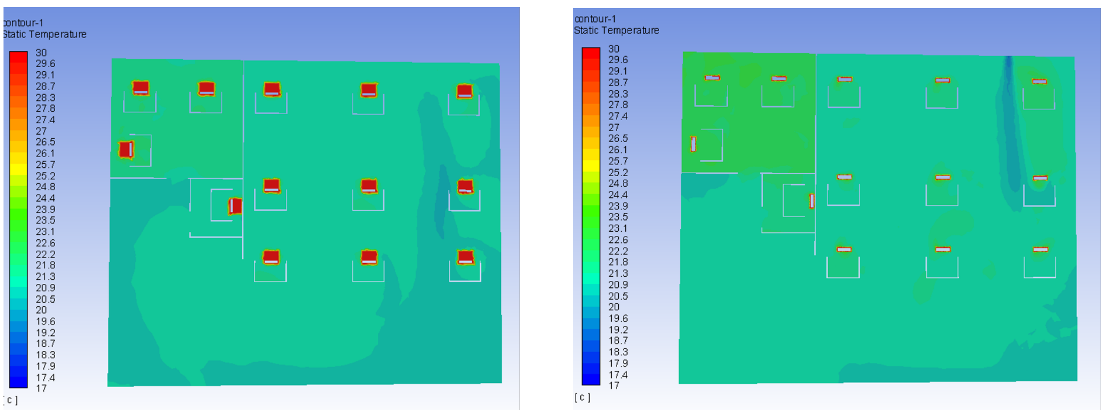
Figure 6.7: Air velocity contour in z direction during Scenario 2 of NV

6.5.2.2 Room Temperature and Relative Humidity

The temperature distribution between the three zones within the office space under Scenario 2 of NV conditions is shown in Figures 6.8. These figures highlight the spatial temperature variations influenced by air inflow from the open window and heat sources such as occupants and equipment.

The large office (Zone 1), with direct airflow from the open window, maintains cooler temperatures between 20 °C and 21 °C in most regions. However, hotspots located near the occupants and heat-emitting devices exhibit temperatures around 23 °C to 24 °C. In contrast, Zones 2 and 3 experience higher temperatures, ranging between 24 °C and 25 °C, due to limited airflow penetration and poor vertical mixing.

The general temperature distribution reveals areas of potential discomfort, particularly in Zones 2 and 3, where limited airflow results in warmer and stagnant conditions. Although localised cooling is achieved in Zone 1 near the window, insufficient air penetration leads to warmer zones further into the space. These findings highlight the need for additional airflow mechanisms, such as AC or mixed-mode systems, to achieve a uniform temperature distribution and improve TC in all zones.



(a) z = 1 m

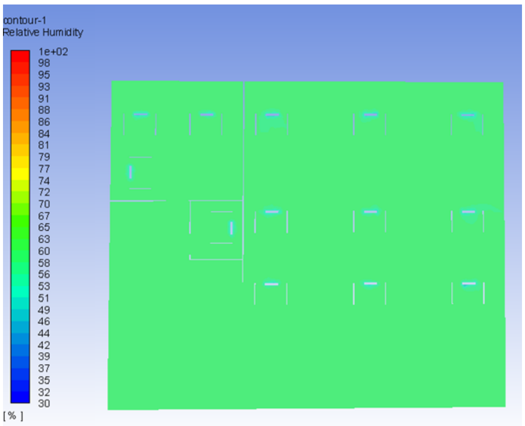
(b) z = 2 m

Figure 6.8: Temperature contour in z direction during Scenario 2 of NV

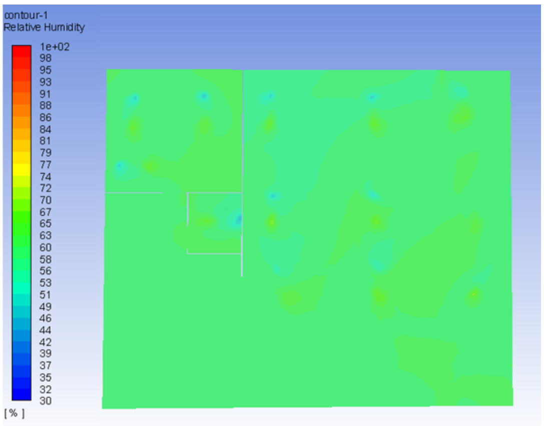
The distribution of RH in the three office zones in Scenario 2 provides insights into moisture regulation and its interaction with air circulation, the presence of the occupant and electronic equipment. Figures 6.9 illustrate the spatial variation of RH between different zones, highlighting areas with potential imbalances.

Most areas show RH levels of around 65%, with certain localised regions reaching up to 70%. These higher humidity concentrations are observed near individuals, electronic equipment, and corners, where airflow may be less effective in dispersing moisture. The elevated RH is consistent with the continuous influx of high-humidity outdoor air, especially in areas where NV dominates.

In general, the findings indicate that while NV can achieve a reasonable air distribution, the high humidity of the incoming outdoor air imposes a challenge in maintaining optimal indoor RH levels.



(a) z = 1 m



(b) z = 2 m

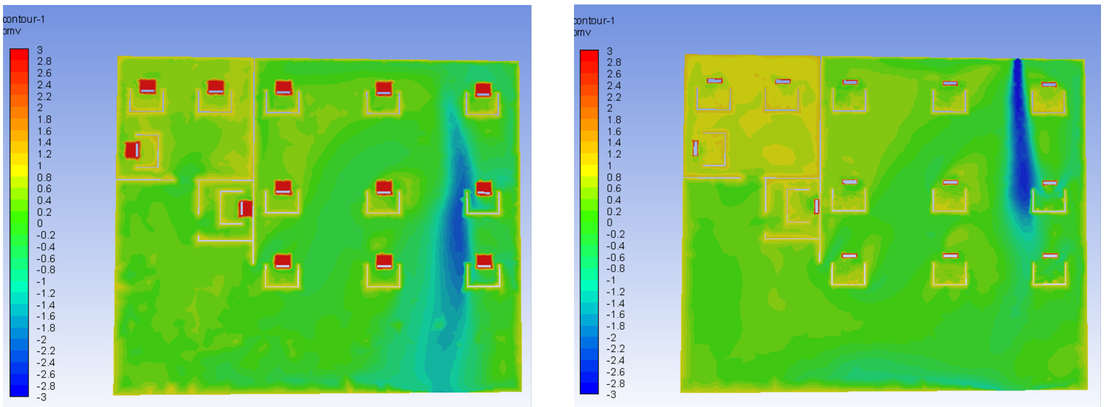
Figure 6.9: RH contour in z direction during Scenario 2 of NV

6.5.2.3 Predicted Mean Vote and Predicted Percentage of Dissatisfied

The distribution of PMV values in the three office zones in Scenario 2 reflects the influence of NV and localised heat sources on TC, as shown in Figures 6.10.

The results highlight that Zone 1 maintains comfortable thermal conditions, with PMV values ranging between 0 and 0.8. In contrast, Zones 2 and 3 exhibit higher PMV values, reaching 1.4, particularly in areas far from the open window and near heat sources.

The PMV variations observed across the zones underscore the importance of effective airflow distribution in naturally ventilated spaces. Zone 1 benefits from the open window, maintaining acceptable TC with minimal warm sensations. However, Zones 2 and 3 experience higher PMV values, which suggests that the occupants in these areas are likely to feel slightly warm. To address this problem, the implementation of additional airflow mechanisms or mixed-mode ventilation could help to balance the thermal environment and ensure uniform occupant comfort in the office space.



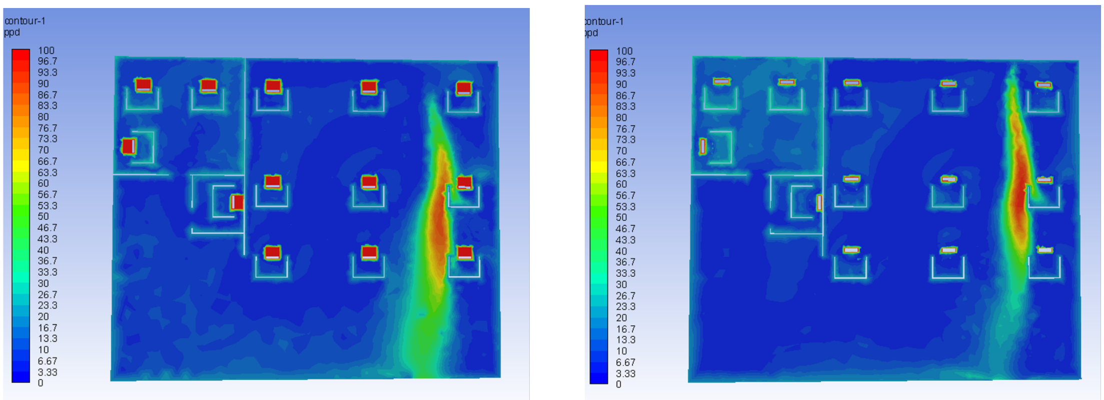
(a) z = 1 m (b) z = 2 m

Figure 6.10: PMV contour in z direction during Scenario 2 of NV

The distribution of PPD corresponds directly to the previously analysed PMV values, highlighting areas where occupants may express discomfort due to variations in thermal conditions and airflow patterns. Figures 6.11 illustrate the distribution of PPD in the different offices in Scenario 2 of NV conditions.

Zones 2 and 3 show PPD values that reach 40% in specific areas, particularly near occupants and heat-generating sources. In contrast, most of the areas in Zone 1 maintain PPD levels below 20%, demonstrating more effective NV in this zone due to the proximity of the open window.

The results highlight that while NV is effective in Zone 1, it does not provide uniform TC throughout the office. Higher PPD values in Zones 2 and 3 suggest localised airflow issues and heat retention, which contribute to occupant discomfort. To address these issues, mixed-mode ventilation or additional passive airflow mechanisms should be considered, such as strategically placed openings or fans. By mitigating localised heat buildup and improving air distribution, overall TC can be enhanced, reducing PPD values to more acceptable levels and ensuring a more comfortable working environment throughout the office space.



(a) z = 1 m

(b) z = 2 m

Figure 6.11: PPD contour In z direction during Scenario 2 of NV

6.5.3 Scenario 3

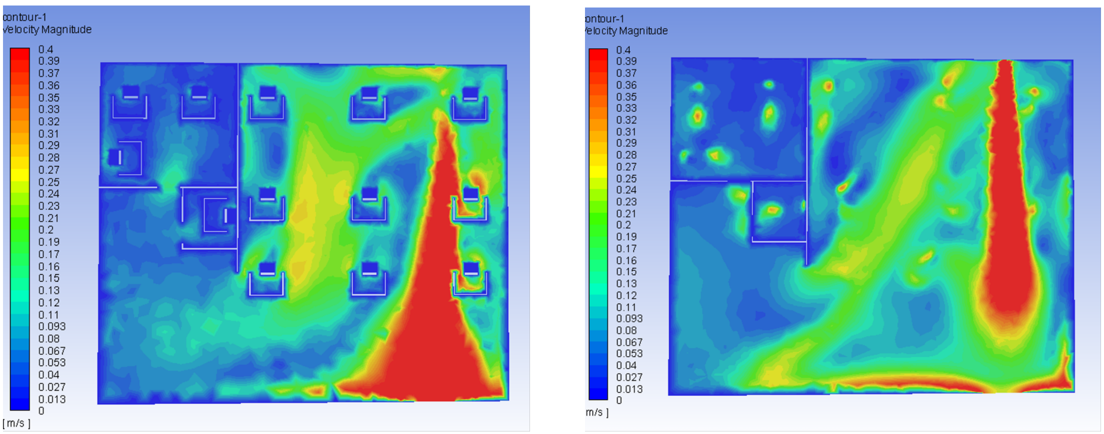
The air velocity distribution across the three office zones under NV in Scenario 3 provides critical information on the uniformity of airflow and the overall efficiency of NV characterised by the opening of Window 4, with the outdoor air entering at a velocity of 3 m/s and a humidity level of 0.0083. The inlet air temperature was set to 19 °C in Ansys to represent realistic summer conditions.

6.5.3.1 Air Velocity Pattern

Figures 6.12 illustrate airflow characteristics in different zones, highlighting areas of effective ventilation, potential stagnation, and deviations from the optimal air distribution. The simulated air velocity within the office space ranged between 0 and 0.4 m/s, with localised airflow patterns that highlight both well-ventilated and stagnant zones.

The highest velocities, exceeding 0.3 m/s, are concentrated near the window and the back row of the occupants in Zone 1. The airflow velocity decreases progressively in Zones 2 and 3, with large portions of these areas displaying stagnant airflow where values range between 0.02 and 0.12 m/s.

In summary, the velocity analysis for Scenario 3 reveals that while the increase in outdoor air velocity improves airflow in areas directly exposed to it, large portions of Zones 2 and 3 suffer from inadequate air circulation. However, this scenario performs better air velocity, even in Zones 2 and 3, compared to the previous scenarios. These findings highlight the need for additional ventilation measures, such as fans or improved NV layouts in Zones 2 and 3, to ensure effective airflow and pollutant dispersion throughout the space.



(a) z = 1 m (b) z = 2 m

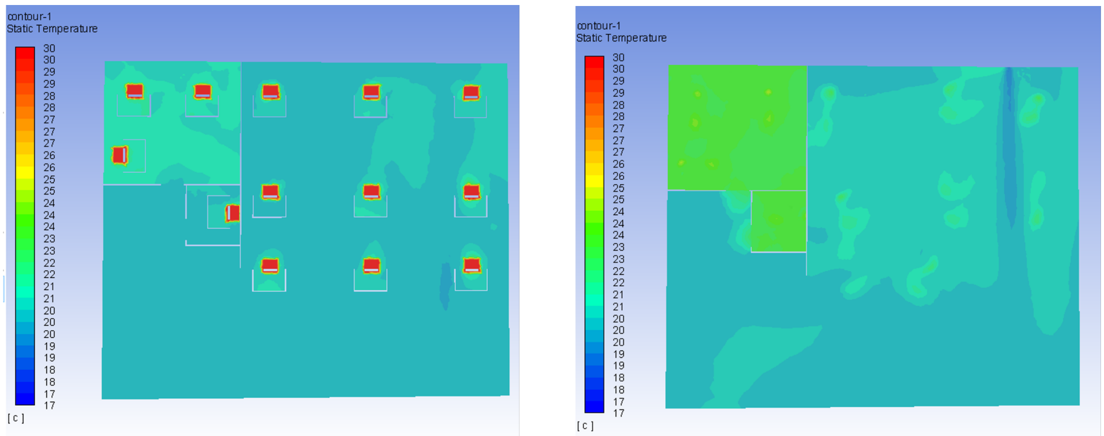
Figure 6.12: Air velocity contour in z direction during Scenario 3 of NV

6.5.3.2 Room Temperature and Relative Humidity

The temperature distribution between the three zones within the office space under Scenario 3 of NV conditions is shown in Figures 6.13. These figures highlight the spatial temperature variations influenced by air inflow from the open window and heat sources such as occupants and equipment.

Zone 1 consistently maintains temperatures between 20 °C and 21 °C, except for minor localised hotspots near occupants and heat sources. In Zones 2 and 3, the temperatures reach 22 °C in some areas but remain within acceptable comfort thresholds. Compared to Scenarios 1, 2, and 3, this scenario demonstrates better thermal performance, with reduced overheating and more balanced temperature levels.

The general results reveal that NV in this scenario effectively stabilises the room temperature in all zones, maintaining values within the comfort range. Zones 2 and 3 benefit from cooler conditions and improved TC compared to previous scenarios, highlighting the importance of optimised NV strategies to achieve uniform indoor climate control.



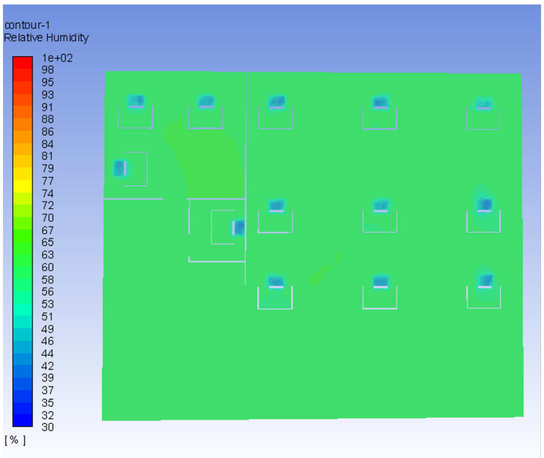
(a) z = 1 m (b) z = 2 m

Figure 6.13: Temperature contour in z direction during Scenario 3 of NV

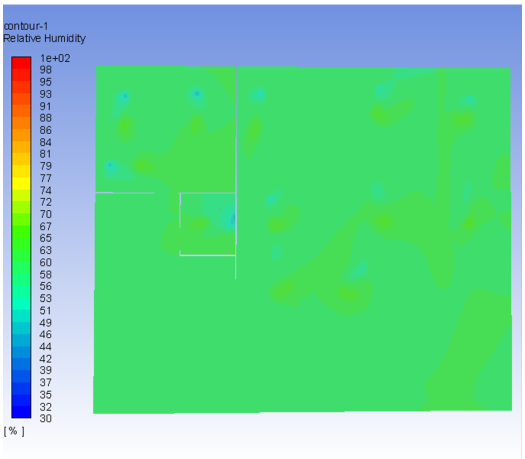
The distribution of RH in the three office zones in Scenario 3 provides insights into moisture regulation and its interaction with air circulation, including the presence of the occupant and electronic equipment. Figures 6.14 illustrate the spatial variation of RH between different zones, highlighting areas with potential imbalances.

Most of the areas in the three zones exhibit RH values ranging from 60% to 70%, except for localised regions near heat sources, where RH levels may momentarily exceed this range. Consistent humidity levels are attributed to the continuous inflow of moist outdoor air, which stabilises the moisture content within the spaces.

In general, the distribution of RH across the office spaces in Scenario 3 demonstrates the effectiveness of NV in maintaining indoor humidity conditions within acceptable comfort levels. The slight elevations in localised regions suggest the potential benefit of mixed-mode ventilation or dehumidification systems to further optimise indoor moisture control and prevent long-term moisture accumulation.



(a) z = 1 m



(b) z = 2 m

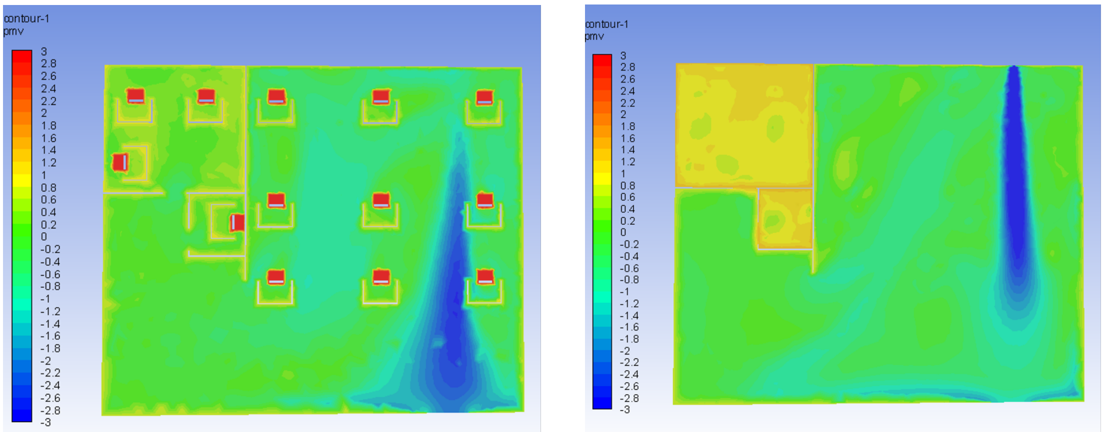
Figure 6.14: RH contour in z direction during Scenario 3 of NV

6.5.3.3 Predicted Mean Vote and Predicted Percentage of Dissatisfied

The distribution of PMV values in the three office zones in Scenario 3 reflects the influence of NV and localised heat sources on TC, as shown in Figures 6.15.

Zone 1 demonstrates the most stable and comfortable conditions, with PMV values ranging from -1.6 to 0.6, signifying predominantly neutral thermal sensations. Zones 2 and 3 exhibit PMV values of up to 1.4 in localised areas, which reflects slightly warmer conditions. Despite these warm spots, both zones show notable improvements in TC compared to Scenarios 1, 2, and 3.

In general, the PMV analysis underscores the effectiveness of NV in Scenario 4, with most areas maintaining PMV values within the recommended comfort range of -1.0 to 1.0. The combination of increased airflow and reduced heat accumulation enhances the thermal environment, creating a more balanced and comfortable indoor environment. Although minor localised discomfort remains in Zones 2 and 3, overall conditions in all zones show significant improvements, which highlights the success of NV in optimising indoor TC.



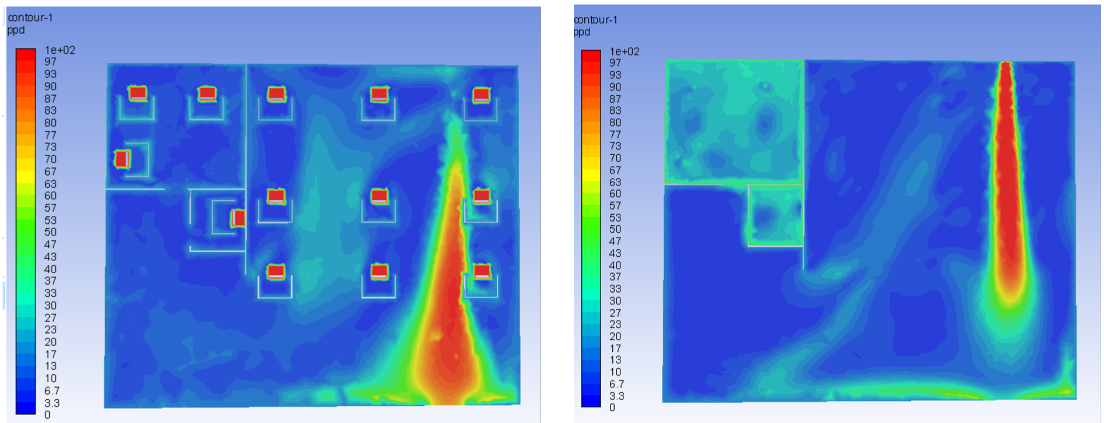
(a) z = 1 m (b) z = 2 m

Figure 6.15: PMV contour in z direction during Scenario 3 of NV

The distribution of PPD corresponds directly to the previously analysed PMV values, highlighting areas where occupants may express discomfort due to variations in thermal conditions and airflow patterns. Figures 6.16 illustrate the distribution of PPD in the different offices in Scenario 3 of NV conditions.

All three zones generally maintain low PPD values, primarily below 20%, reflecting a high level of TC throughout much of the space. However, notable exceptions include a central area within Zone 1 and near the entrance door, where PPD values peak at 90%. These elevated levels of dissatisfaction are likely due to inadequate airflow in these areas, coupled with localised heat accumulation.

In general, the PPD analysis shows significant improvements in office TC compared to previous scenarios, with NV effectively reducing dissatisfaction in most areas. However, the persistence of high PPD values in certain regions suggests the need for targeted airflow interventions, such as additional ventilation openings or localised fans, to further optimise comfort and minimise dissatisfaction.



(a) z = 1 m (b) z = 2 m

Figure 6.16: PPD contour in z direction during Scenario 3 of NV

6.5.4 Scenario 4

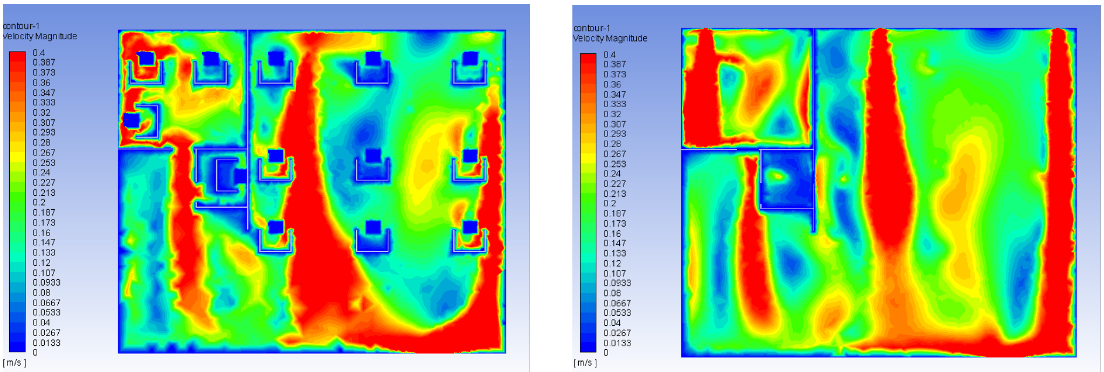
The air velocity distribution across the three office zones under NV in Scenario 4 provides critical information on the uniformity of airflow and the overall efficiency of NV characterised by opening Window 1, Window 6, and Window 9, with outdoor air entering at a speed of 3 m/s and a humidity level of 0.0115. The inlet air temperature was set to 17.5 °C in Ansys to represent realistic summer conditions. The selection of multiple windows positioned at different locations enables better CV and airflow dynamics compared to previous scenarios.

6.5.4.1 Air Velocity Pattern

The air velocity distribution across the three office zones in Scenario 4 of NV highlights the impact of strategically placed open windows on airflow patterns and general ventilation, as shown in Figures 6.17.

Airflow remains generally stable, with values averaging around 0.2 m/s to 0.4 m/s in most areas. The highest velocities are observed near the windows and occupant regions, while areas near the occupants sitting in the central section and in Zone 3 experience reduced airflow, with velocities dropping as low as 0.04 m/s. This reduction is attributed to the limited direct airflow pathways that reach these areas.

The air velocity distribution analysis for Scenario 4 highlights improved ventilation performance due to the optimised placement of multiple open windows. The increased airflow ensures minimal stagnation and promotes a more uniform air distribution across most zones, effectively outperforming the previous scenarios. This scenario demonstrates the best overall air velocity performance, contributing to improved ventilation in all zones.



(a) z = 1 m   (b) z = 2 m

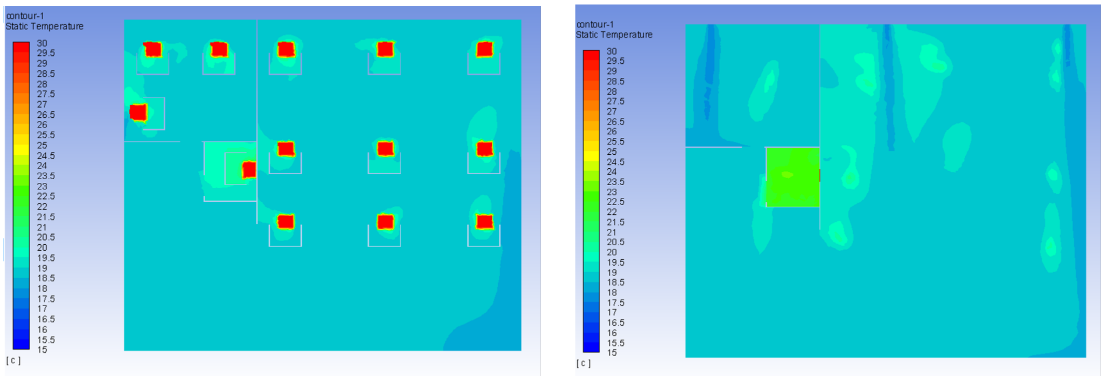
Figure 6.17: Air velocity contour in z direction during Scenario 4 of NV

6.5.4.2 Room Temperature and Relative Humidity

The distribution of room temperature across the three office zones in Scenario 4 demonstrates the effectiveness of enhanced NV and cross-flow airflow to maintain TC, as depicted in Figures 6.18.

Most of the area in all zones exhibits the most consistent and favourable conditions, with temperatures ranging between 19.5 °C and 21 °C in most areas. Zone 3 shows slightly higher temperatures in localised regions, peaking at 22 °C, but remains within the comfortable temperature range.

The temperature distribution analysis for Scenario 4 highlights the effectiveness of strategically placed open windows, which provide ample airflow to minimise heat accumulation and maintain overall TC. This scenario demonstrates improved temperature regulation and a more comfortable indoor environment compared to previous scenarios.



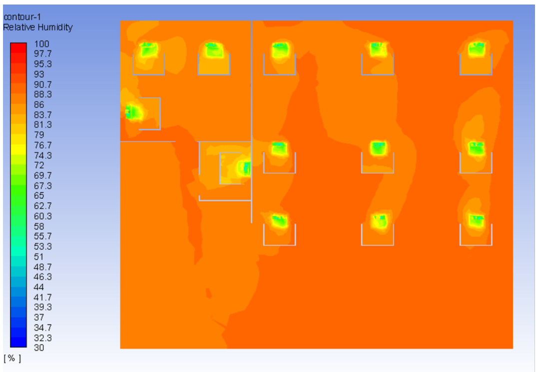
(a) z = 1 m (b) z = 2 m

Figure 6.18: Temperature contour in z direction during Scenario 4 of NV

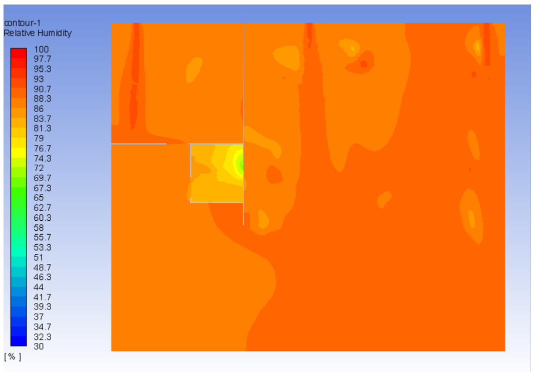
The distribution of RH in the three office zones in Scenario 4 highlights the impact of NV on influencing moisture levels and the presence of localised variations, as illustrated in Figures 6.19.

All three zones maintain elevated RH levels predominantly between 76% and 90%, reflecting inadequate moisture regulation. Zone 3 exhibits slightly lower RH levels compared to Zones 1 and 2 due to reduced airflow limiting excessive moisture transport.

The relative humidity distribution analysis for Scenario 4 indicates that while NV improves airflow, it inadvertently contributes to increased moisture levels in the office space. The strategic placement of multiple open windows has caused excessive humidity build-up, creating unfavourable indoor conditions compared to previous scenarios. These results emphasise the need for improved moisture control mechanisms to achieve a balanced indoor environment conducive to occupant comfort.



(a) z = 1 m



(b) z = 2 m

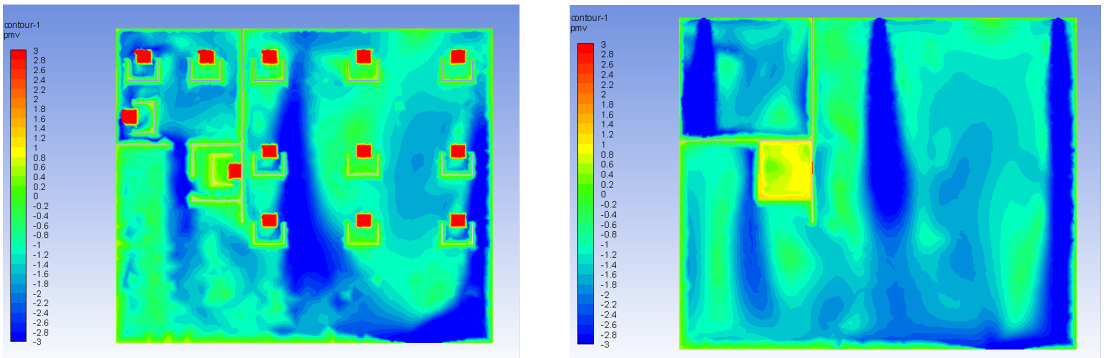
Figure 6.19: RH contour in z direction during Scenario 4 of NV

6.5.4.3 Predicted Mean Vote and Predicted Percentage of Dissatisfied

The distribution of PMV values in the three office zones in Scenario 4 reflects the influence of NV and localised heat sources on TC, as shown in Figures 6.20.

Zones 1 and 2 exhibit predominantly cold conditions, with PMV values ranging between -2.5 and 0.2, indicating slight to moderate cool sensations. The first and last columns are particularly cold, while those in the central area feel slightly cooler. In Zone 2, areas with limited airflow result in slightly higher PMV values, leading to warmer sensations compared to the other zones. Zone 3 demonstrates an improved thermal sensation profile, maintaining a more balanced environment compared to Zones 1 and 2.

The PMV analysis for Scenario 4 reveals that the combination of NV and cross-flow airflow has a negative impact on overall TC. Excess cooling, coupled with uneven airflow distribution, results in an indoor environment with limited areas of comfort and significant zones of discomfort. Compared to previous scenarios, this setup exhibits a slight deterioration in thermal regulation, highlighting the need for further optimisation to achieve a comfortable environment for the occupants.



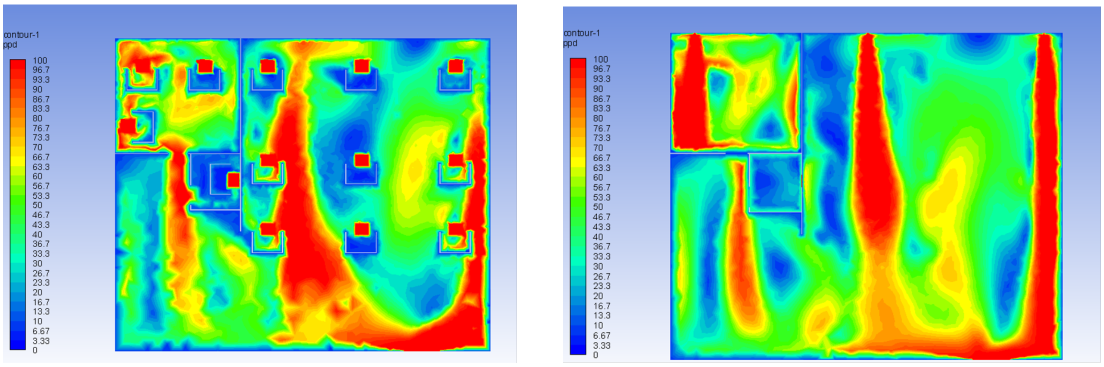
(a) z = 1 m (b) z = 2 m

Figure 6.20: PMV contour in z direction during Scenario 4 of NV

The distribution of PPD corresponds directly to the previously analysed PMV values, highlighting areas where occupants may express discomfort due to variations in thermal conditions and airflow patterns. Figures 6.21 illustrate the distribution of PPD in the different offices in Scenario 4 of NV conditions.

Zone 1 shows moderate to high dissatisfaction, with values predominantly between 10% and more than 90%. Zone 2 shows a more pronounced dissatisfaction in the upper regions, reaching over 90% due to airflow-induced cold spots. In contrast, Zone 3 shows considerably lower dissatisfaction, with most areas maintaining PPD values below 20%, reflecting the relative thermal stability of the zone and limited exposure to intense airflow.

The PPD analysis for Scenario 4 reveals that NV and cross-flow airflow produce mixed results in TC. Although airflow effectively prevents heat accumulation, it simultaneously introduces excessive cooling in several areas, leading to widespread dissatisfaction. Compared to previous scenarios, this setup results in greater overall dissatisfaction, underscoring the need for better airflow management and a more controlled distribution to enhance occupant comfort.



(a) z = 1 m (b) z = 2 m

Figure 6.21: PPD contour in z direction during Scenario 4 of NV

6.5.4.4 Aerosol Dispersion and Infection Risk

Infection risk analysis was exclusively conducted for Scenario 4 because it represented the most effective cross-ventilation (CV) configuration in terms of airflow distribution and air exchange rates, as established in section 6.5.4.1. Among all the evaluated scenarios, Scenario 4 demonstrated the highest air velocities and the greatest potential for particle transport across different zones, making it the most critical case for assessing the implications of natural ventilation on airborne virus transmission. Assessing infection risk under less ventilated scenarios (e.g., Scenarios 1 to 3) would not offer additional insights, as stagnant airflow zones in those cases already indicate poor dispersion and higher pollutant retention. Therefore, Scenario 4 was selected as a representative high-performance NV case to examine how increased airflow influences aerosol transport and cross-contamination potential in a shared office space.

Coughing is one of the primary ways through which infectious aerosols are expelled from the human respiratory system, posing a significant risk of airborne virus transmission in enclosed spaces. In the current analysis, the particle dispersion dynamics due to coughing were studied in Scenario 4, where NV and cross-flow airflow play a central role. A coughing velocity of 11.8 m/s was applied and the analysis focused on the spatial and temporal movement of the particles of four different occupants. The following results highlight the extent of particle spread in the X, Y, and Z directions, evaluating how airflow impacts their dispersion within the indoor environment. Figure 6.22 demonstrates the spatial distribution of aerosols expelled by the first individual during coughing. The expelled particles initially exhibit a concentrated forward movement before undergoing significant dispersion influenced by indoor airflow. A dense accumulation is observed near the source; however, the particles spread widely, especially toward the occupants sitting in the path of the airflow.

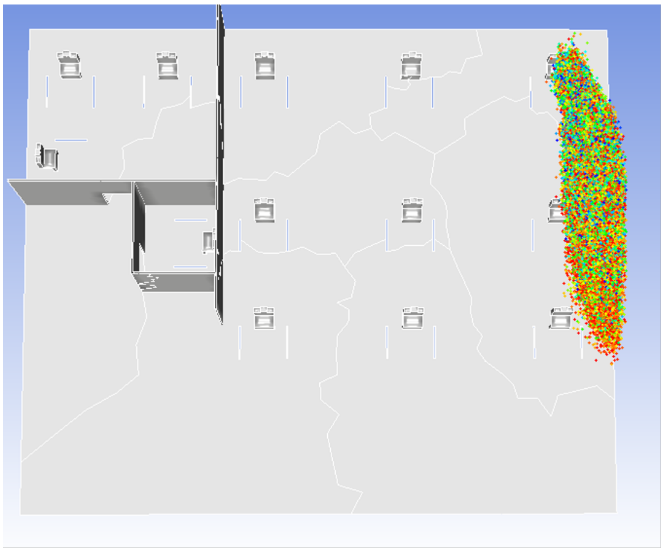


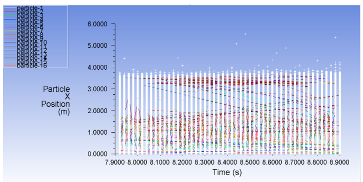
Figure 6.22: Particle transmission from the first infected individual during coughing.

Figure 6.23 illustrates the dispersion of aerosols by coughing in the X, Y, and Z directions for the first individual during NV.

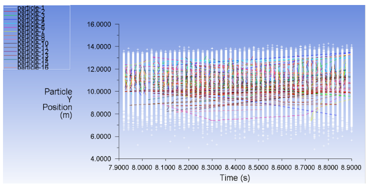
In X direction dispersion, as shown in Figure 6.23-(a), particles exhibit an initial rapid displacement, primarily due to the high forward velocity of the sneeze. The particles remain predominantly within the range of 0 to 3.5 m (indicating a transmission distance of approximately 3.5 m), demonstrating limited lateral spread under existing airflow conditions.

Figure 6.23-(b) highlights the diffusion of lateral particles in the Y direction with displacement values ranging between 7 and 13 m (indicating a transmission distance of approximately 6 m). This indicates significant horizontal spread as a result of interactions with airflow, allowing particles to reach distant areas within the room.

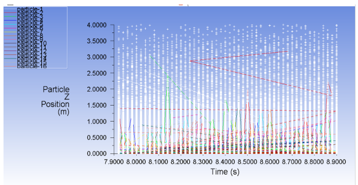
Figure 6.23-(c) shows the vertical particle distribution as shown in the Z direction between 0 m and 3 m (indicating a transmission distance of approximately 3 m), corresponding to the breathing zone of most of the inhabitants. Minimal upward or downward dispersion is observed beyond this range, highlighting the high transmission risk within this critical zone.



(a) X direction



(b) Y direction



(c) Z direction

Figure 6.23: Aerosol dispersion through coughing in X, Y,and Z directions for the first individual during NV.

Figure 6.24 demonstrates the spatial distribution of aerosols emitted by the second individual during coughing. The expelled particles exhibit strong initial forward momentum before dispersing and spreading under the influence of indoor airflow. A dense concentration of particles is observed around the source, with a broader dispersion in the area in front of the infected individual due to NV.

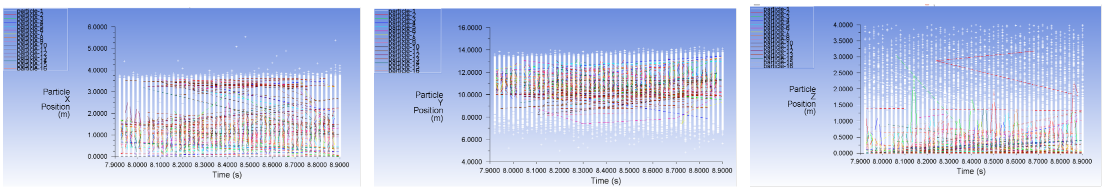
Figure 6.24: Particle transmission from the second infected individual during coughing.

Figure 6.25 illustrates the dispersion of aerosols by coughing in the X, Y, and Z directions for the second individual under NV.

Figure 6.25-(a) shows the displacement of the particles in the X direction over time. The particles initially move forward rapidly due to the high velocity of the cough, they then decelerate as they interact with turbulent airflow. The particles remain predominantly within the range of 0 to 3.5 m (indicating a transmission distance of approximately 3.5 m), indicating limited lateral diffusion along the X axis.

The dispersion in the Y direction, as presented in Figure 6.25-(b), highlights the lateral spread of the particles throughout the room. The particles disperse between 8 and 12 m (indicating a transmission distance of approximately 4 m), suggesting that significant lateral movement occurs due to turbulent interactions and natural airflow. This diffusion increases the risk of exposure to multiple occupants within the surrounding area.

The dispersion in the Z direction, illustrated in Figure 6.25-(c), shows how vertical particle movement is affected by airflow patterns and gravity. The majority of particles remain between 0 and 3 m (indicating a transmission distance of approximately 3 m), within the breathing zone of seated and standing individuals. Minimal vertical displacement beyond this range is observed, indicating that the particles largely remain suspended within the critical transmission height levels, posing a risk of respiratory exposure.



(a) X direction (b) Y direction (c) Z direction

Figure 6.25: Aerosol dispersion through coughing in X, Y,and Z directions for the second individual during NV.

Figure 6.26 demonstrates the spatial distribution of aerosols emitted by the third individual. The particles show a strong forward projection, rapidly dispersing and diffusing under the influence of airflow from the window. A dense cluster of particles is initially observed near the source before scattering across the occupied space, increasing the likelihood of exposure of nearby individuals.

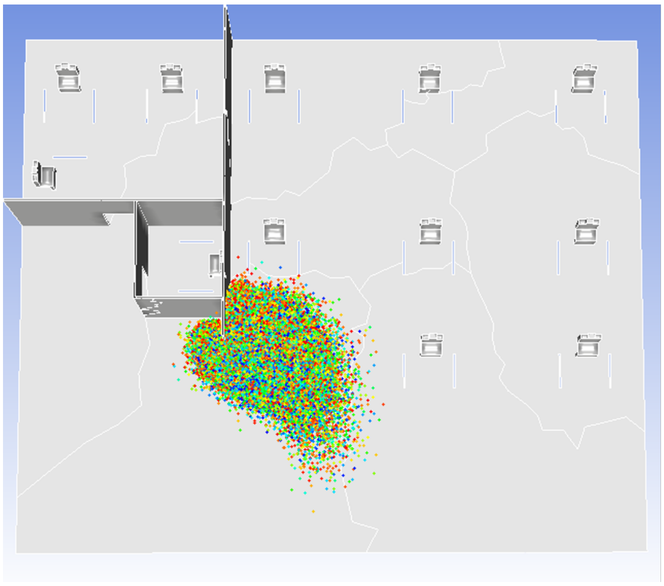


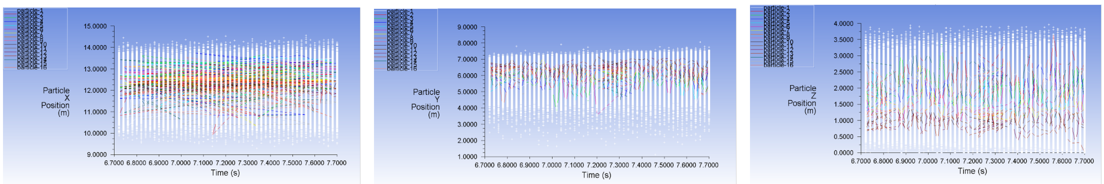
Figure 6.26: Particle transmission from the third infected individual during coughing.

Figure 6.27 illustrates the aerosol dispersion along the X, Y, and Z directions during the coughing event for the third individual.

Figure 6.27-(a) displays the movement of the particles in the X direction over time. The particles show a rapid initial forward motion due to the high velocity of the cough. As they propagate, most of the particles remain within the 10 to 13.5 m range (indicating a transmission distance of approximately 3.5 m), reflecting a limited forward spread due to airflow redirection from nearby walls. The restricted forward range mitigates exposure to distant occupants but contributes to localised density in the immediate area.

In the Y direction (Figure 6.27-(b)), particle displacement ranges between 4 and 7 m (indicating a transmission distance of approximately 3 m). Lateral diffusion is more prominent because of turbulent flow interactions, leading to moderate horizontal dispersion. This pattern indicates a significant risk of exposure for occupants seated in proximity to the infected individual.

The vertical displacement of the particles (Figure 6.27-(c)) is influenced by gravitational settling and airflow buoyancy. The particles remain predominantly within a height of 0.5 m to 3 m (indicating a transmission distance of approximately 2.5 m), corresponding to the breathing level of seated and standing individuals. The minimal movement of particles beyond this height indicates that the particles are largely concentrated in regions that are critical to respiratory exposure.



(a) X direction (b) Y direction (c) Z direction

Figure 6.27: Aerosol dispersion through coughing in X, Y,and Z directions for the third individual during NV.

Figure 6.28 demonstrates the spatial distribution of aerosols emitted by the fourth individual. The expelled particles exhibit rapid initial movement, followed by dispersion influenced by airflow patterns and the surrounding ventilation. A dense concentration of particles is observed near the source, particularly in the immediate area, before they diffuse and spread to nearby areas, affecting the occupants in proximity.

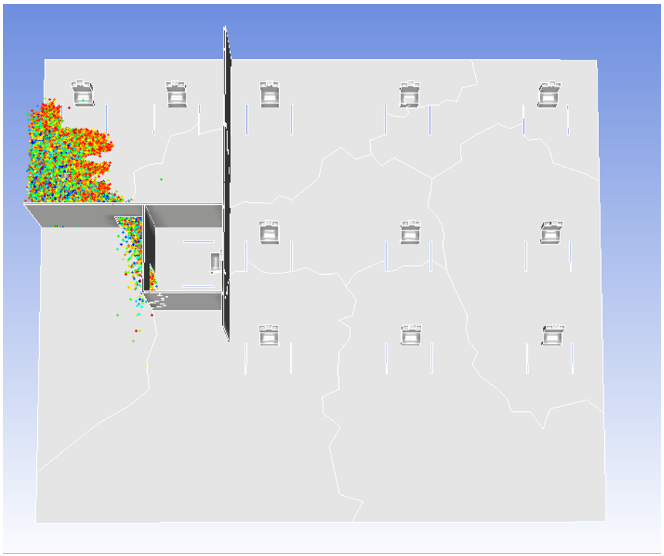


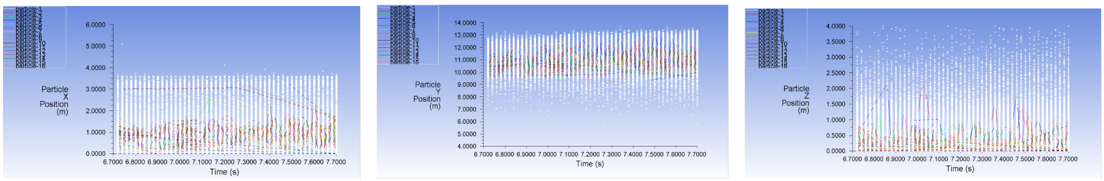
Figure 6.28: Particle transmission from the fourth infected individual during coughing.

Figure 6.29 illustrates the aerosol dispersion in the X, Y, and Z directions for the fourth individual during NV.

Figure 6.29-(a) shows the displacement of the particles in the X direction over time. The particles initially exhibit forward motion but encounter significant deceleration and dispersion as they interact with air flow and structural elements. The displacement values range predominantly between 0 and 3 m (indicating a transmission distance of approximately 3 m), indicating limited horizontal movement within the immediate surrounding area.

The dispersion in the Y direction, as shown in Figure 6.29-(b), indicates the lateral spread of the particles with values ranging between 9 m and 12.5 m (indicating a transmission distance of approximately 3.5 m). This range suggests significant lateral movement due to turbulent indoor airflow, which can potentially lead to higher exposure risks among occupants located in the vicinity.

In the vertical (Z) direction, Figure 6.29-(c) highlights how particle movement is affected by gravity and buoyant forces. The majority of particles are concentrated between 0 and 1.5 m in height (indicating a transmission distance of approximately 1.5 m), corresponding to the breathing zones of seated and standing individuals. Minimal upward or downward movement beyond this range is observed, suggesting that the majority of particles remain within a critical zone for transmission risks.



(a) X direction (b) Y direction (c) Z direction

Figure 6.29: Aerosol dispersion through coughing in X, Y,and Z directions for the fourth individual during NV.

Sneezing is another major mechanism responsible for the evaporation of high-speed infectious aerosols, posing a higher risk of rapid airborne disease transmission. Compared to coughing, sneezing can eject particles at much higher velocities, leading to a broader and faster spread. In this analysis, a sneezing velocity of 70 m/s was applied in Scenario 4, where NV and cross-flow airflow significantly affect the movement of expelled particles. This study focused on four different infected individuals to assess the spatial and temporal dispersion of particles along the X, Y, and Z directions within the indoor environment. Figure 6.30 demonstrates the spatial distribution of aerosols emitted by the first individual. The expelled particles exhibit strong initial forward movement before dispersing and spreading under the influence of indoor airflow. A dense concentration of particles is observed in the immediate vicinity of the source but as the particles travel further they become more widely distributed, specifically to the occupants sitting in front of the infected individual.

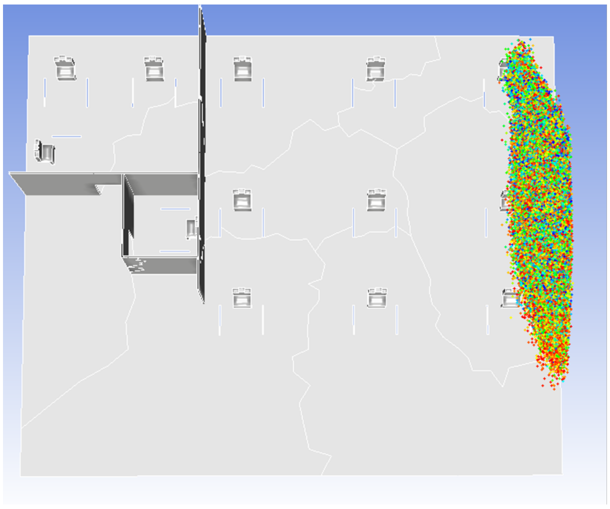


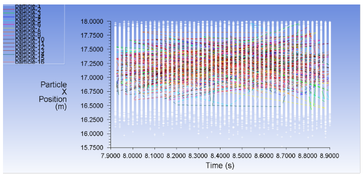
Figure 6.30: Particle transmission from the first infected individual during sneezing.

Figure 6.31 illustrates the aerosol dispersion in the X, Y, and Z directions for the first individual during NV.

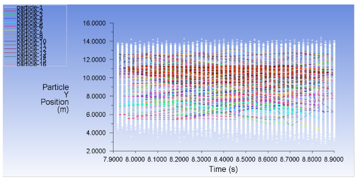
Figure 6.31-(a) shows the displacement of the particles in the X direction over time. The particles initially move rapidly due to the forward momentum of the sneeze but begin to decelerate as they encounter resistance and airflow redirection. Most of the particles remain within a range of 16.5 to 18 m (indicating a transmission distance of approximately 1.5 m), demonstrating limited lateral spread under the existing airflow conditions.

The dispersion in the Y direction, as seen in Figure 6.31-(b), highlights how the particles laterally distribute. The displacement values range between 5 and 13 m (indicating a transmission distance of approximately 8 m), indicating that although the initial motion occurs primarily forward, the particles undergo notable lateral diffusion due to interactions with turbulent airflow. This lateral dispersion increases the potential for exposure in multiple zones of occupancy. In the vertical (Z) direction, Figure 6.31-(c) reveals how particle movement is affected by gravitational settling and buoyant airflow. Most particles remain concentrated between

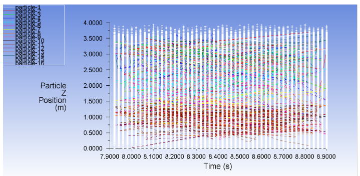
0 and 3.5 m in height (indicating a transmission distance of approximately 3.5 m), corresponding to the breathing zone of seated and standing occupants. Minimal upward or downward dispersion is observed beyond this range, suggesting that the particles are largely contained within a height range that is critical to transmission risks.



(a) X direction



(b) Y direction



(c) Z direction

Figure 6.31: Aerosol dispersion in X, Y,and Z directions for the first individual during NV.

Figure 6.32 shows the concentrated cloud of particles that moves out of the second individual's position and spreads through the central and nearby areas of the office. The particle concentration shows a broad spread in the X and Y directions, but the vertical movement (Z axis) remains moderate, indicating limited vertical dispersion.

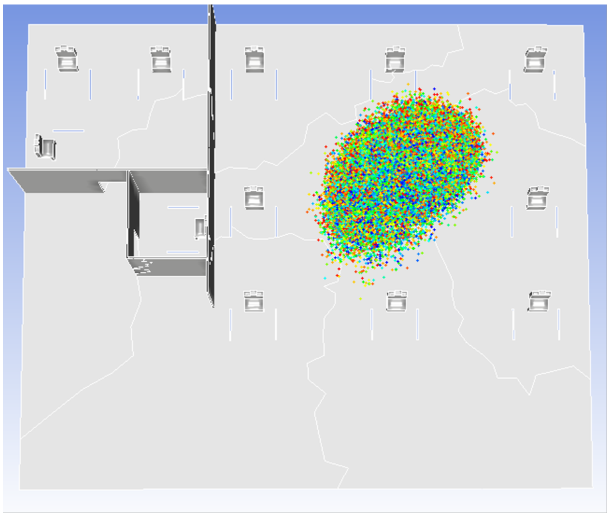


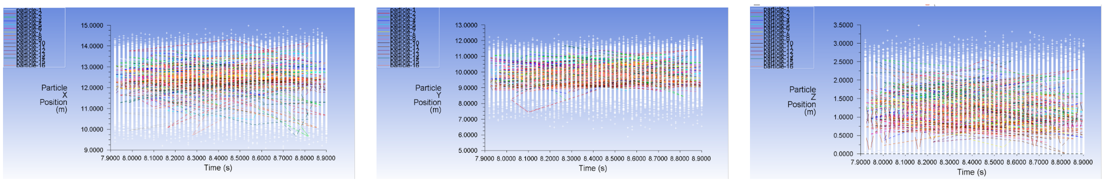
Figure 6.32: Particle transmission from the second infected individual during sneezing.

Figure 6.33 illustrates the aerosol dispersion in the X, Y, and Z directions for the second individual during NV.

Figure 6.33-(a) shows the particle displacement the X-position tracking over time reveals steady particle advancement within a confined range from 10 to 14 metres (indicating a transmission distance of approximately 4 m). This relatively moderate lateral spread suggests that the airflow did not generate excessive turbulence in this direction, leading to limited particle displacement.

The dispersion in the Y direction, as seen in Figure 6.33-(b), highlights how the particles exhibit a more dynamic spread, with values ranging between 8 and 11 m (indicating a transmission distance of approximately 3 m). The variation highlights how natural airflow patterns within the office space interact with the particles, causing minor deflections, but maintaining overall trajectory consistency.

In the vertical (Z) direction, Figure 6.33-(c) reveals how particle movement is affected by gravitational settling and buoyant airflow. Most particles remain concentrated between 0 and 2.5 m in height (indicating a transmission distance of approximately 2.5 m), corresponding to the breathing zone of the seated and standing occupants. Minimal upward or downward dispersion is observed beyond this range, suggesting that the particles are largely contained within a height range critical to transmission risks.



(a) X direction (b) Y direction (c) Z direction

Figure 6.33: Aerosol dispersion in X, Y,and Z directions for the second individual during NV.

Figure 6.34 shows the distribution of the particles released from the third individual's position. The particles are concentrated and dispersed primarily around the source location and downstream, reflecting the combined influence of airflow and initial particle velocity. Most of the particles remain within the vicinity of the infected individual, with limited transport across the room.

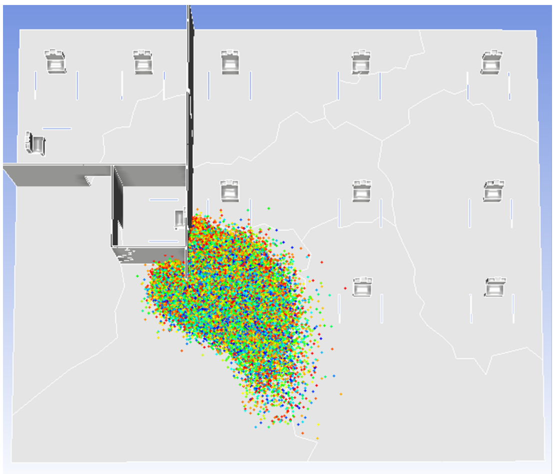
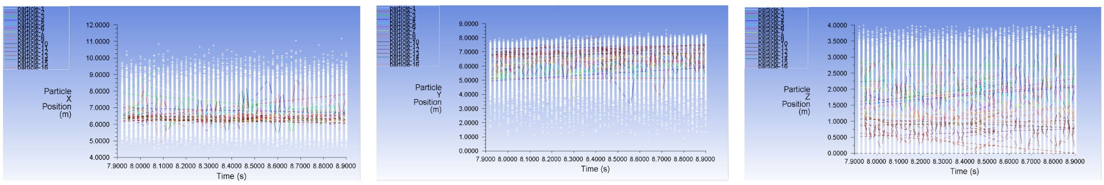


Figure 6.34: Particle transmission from the third infected individual during sneezing..

Figure 6.35 illustrates the aerosol dispersion in the X, Y, and Z directions for the third individual during NV.

As illustrated in Figure 6.35-(a), the longitudinal transport of the particles is relatively contained within the range of 6 to 8.5 m (indicating a transmission distance of approximately 2.5 m), with minor fluctuations observed as time progresses. The overall X movement can travel further due to airflow pushing particles across the horizontal plane. In the dispersion in the Y direction, as seen in Figure 6.35-(b), the lateral spread of the particles varies mainly between 4 and 7.5 m (indicating a transmission distance of approximately 3.5 m). The motion of the particles in this direction reflects the effects of both coughing velocity and cross-flow ventilation, though the distribution remains more compact compared to other infected individuals, possibly due to the specific location of the individual within the room. The vertical dispersion of the particles, shown in Figure 6.35-(c), occurs within the range of 0.25 to 3 m (indicating a transmission distance of approximately 2.75 m). The upward movement of the particles is influenced by the velocity of coughing and the airflow of the room, with the particles reaching a maximum height of approximately 3.5 m before settling down. This distribution pattern indicates moderate vertical spread, potentially increasing the likelihood of inhalation by nearby individuals.



(a) X direction (b) Y direction (c) Z direction

Figure 6.35: Aerosol dispersion in X, Y,and Z directions for the third individual during NV.

Figure 6.36 illustrates the overall particle distribution release from the fourth individual's position. The particles initially form a dense plume near the source, spreading primarily toward the lower left and adjacent areas due to airflow restrictions. The accumulation of particles in this confined region indicates limited ventilation, with a large portion of the particles settling near the origin.

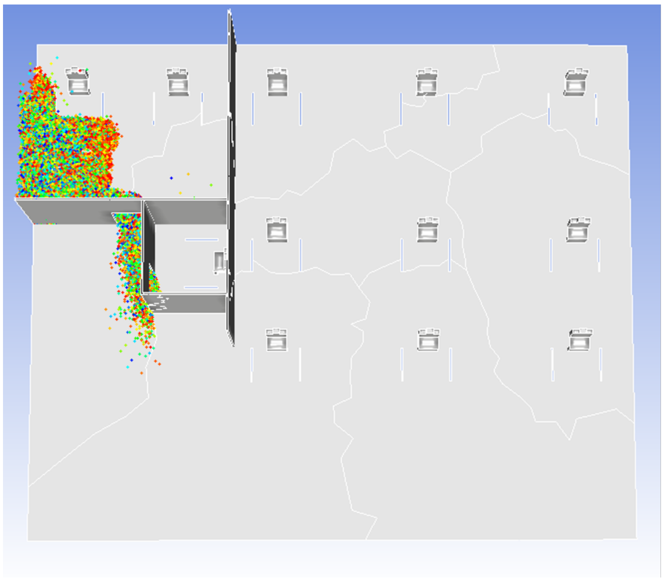
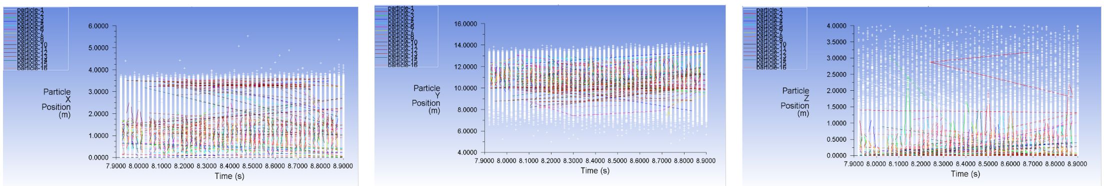


Figure 6.36: Particle transmission from the fourth infected individual during sneezing.

Figure 6.37 illustrates the aerosol dispersion in the X, Y, and Z directions for the fourth individual during NV.

Figure 6.37-(a) shows the movement of the particles along the X axis with time. Most particles remain between 0 and 3.5 m in the initial stage (indicating a transmission distance of approximately 3.5 m), indicating minimal lateral spread. Over time, particles move toward the door and exit into the adjacent zone, driven by the airflow pattern created by the open window and localised air currents. This movement demonstrates a key pathway for particle transport. The spread of particles in the Y axis, depicted in Figure 6.37-(b), reveals that the majority of particles are concentrated within a range of 8 to 13 m (indicating a transmission distance of approximately 5 m). The particles travel through the door and the distribution extends further into adjacent areas, showing how airflow effectively

disperses aerosols beyond the source zone. As shown in Figure 6.37-(c), the movement of the particles along the Z axis mainly ranges between 0 and 2.5 m in height (indicating a transmission distance of approximately 2.5 m). Most particles settle near the floor or at mid-levels, with minimal upward dispersion. This limited vertical movement suggests that vertical air circulation is inadequate, resulting in particle accumulation at breathing levels and lower areas.



(a) X direction (b) Y direction (c) Z direction

Figure 6.37: Aerosol dispersion in X, Y,and Z directions for the fourth individual during NV.

6.6 Discussion

This section provides a comprehensive discussion of the results obtained from the five NV scenarios, focussing on airflow patterns, IAQ, room temperature, RH, TC indices (PMV and PPD), and aerosol dispersion. The findings are compared with the ASHRAE, EN 16798, and ISO 7730 standards for acceptable indoor conditions to identify optimal and suboptimal configurations, and suggest recommendations for improved ventilation performance.

6.6.1 Comparison with ASHRAE, EN 16798, and ISO 7730 Standards

NV scenarios were evaluated against the TC criteria outlined in ASHRAE 55, ISO 7730, and EN 16798. These standards define acceptable PMV and PPD to ensure a comfortable indoor environment. ASHRAE 55 specifies an occupancy satisfaction level of 80%, corresponding to a PMV range of -0.5 to +0.5 and a PPD below 20%, while ISO 7730 and EN 16798 classify comfort into three categories:

- Category A (ISO)/I (EN): PMV within ±0.2 and PPD < 6% (high expectations)
- Category B (ISO)/II (EN): PMV within ±0.5 and PPD < 10% (normal expectations)
- Category C (ISO)/III (EN): PMV within ±0.7 and PPD < 15% (moderate comfort)

The TC performance varied between the scenarios, with CV achieving the best results and SSV showing notable deviations.

In Scenario 1 (summer conditions), Zone 1 achieved PMV values between 0 and 0.5, meeting the ASHRAE and ISO Category B/II guidelines, ensuring that 80% of the occupants felt thermally comfortable. However, Zones 2 and 3 exhibited slightly warm conditions (PMV: 0.4–1.0), with PPD values exceeding 30%, indicating a notable dissatisfaction. Room temperature (20 °C to 22 °C) remained within the ASHRAE guidelines, but RH approached 70%, slightly exceeding the recommended threshold.

Air velocity was another crucial factor affecting comfort. Although ASHRAE 55 recommends indoor airflow velocities between 0.15 and 0.25 m/s, measurements showed that most areas had velocities below 0.1 m/s, indicating insufficient air circulation. However, areas near the open window experienced higher airflows (> 0.2 m/s), increasing the risk of aerosol dispersion and potential virus transmission.

Scenario 2 (also in summer conditions) demonstrated similar TC trends. Zone 1 was aligned with the ASHRAE and ISO standards, with PMV between 0 and 0.5 and occupant satisfaction 80%. However, Zones 2 and 3 again showed slightly warm conditions (PMV: 0.4–1.0, PPD > 30%), highlighting areas of discomfort. Room temperature (20°C to 23°C) remained within ASHRAE limits, but RH exceeded 65%, slightly exceeding comfort recommendations.

The air velocity distribution was mixed. Zone 1 complied mainly with the recommended air flow of ASHRAE of 0.2 m/s, but areas near the window exhibited an excessive air velocity (> 0.3 m/s), while Zones 2 and 3 remained below 0.08 m/s, indicating stagnant airflow and reduced ventilation effectiveness.

Scenario 3 performed best in terms of TC, with PMV values ranging between 0 and 0.5 in the three zones, ensuring the satisfaction of the occupants 80%. The room temperature remained between 20 °C and 23 °C, fully in accordance with the ASHRAE and ISO standards.

However, RH levels remained above 65%, indicating a challenge in humidity control in NV settings, especially in humid outdoor conditions. The air velocity followed similar trends, with Zone 1 maintaining airflow compliance (0.2 m/s), while Zones 2 and 3 had lower velocities (0 to 0.08 m/s), reinforcing the need for a better airflow distribution.

Scenario 4 integrated TC assessments with aerosol dispersion analysis. Although some areas met the ASHRAE guidelines, others deviated due to three open windows creating airflow inconsistencies. PMV ranged from -2 near the windows to +0.5 further into the room, which means that people near the windows experienced excessive cooling (PMV: -2, dissatisfaction > 80%), while those in the interior zones had relatively neutral conditions (PMV < 0.5).

Room temperatures ranged from 20 °C (zones 1 and 2) to 23 °C (Zone 3), according to ASHRAE recommendations. However, RH exceeded 65%, exceeding the upper comfort threshold.

Across all scenarios, air velocity varied significantly depending on location. CV provided sufficient air exchange (0.2 to 0.3 m/s), but SSV created stagnant air pockets (< 0.1 m/s), failing to meet the air velocity criteria of ASHRAE 55 and ISO 7730.

Furthermore, areas near open windows had excessive airflow (> 0.3 m/s), which could increase the risk of viral transmission, because higher speeds disperse infectious aerosols further into the room. This aligns with studies by [332], which highlight the role of airflow in the propagation of viral particles.

TC standards also consider humidity effects, and ASHRAE 55 recommends an RH range of 30 to 60% for occupant comfort. In all of our NV scenarios, RH closely followed outdoor moisture conditions because there was no active dehumidification.

Although ISO 7730 suggests that moderate humidity variations have minimal influence on thermal sensation, ASHRAE 55 emphasises that high RH (> 65%) can reduce perceived air quality and increase discomfort. These findings indicate that NV alone cannot actively regulate humidity, making it less suitable in humid climates unless paired with dehumidification strategies or hybrid ventilation solutions.

6.6.2 Identification of Dead Zones in Natural Ventilation

Dead zones, defined as areas with minimal or stagnant airflow, pose a significant challenge in naturally ventilated environments, leading to inefficient air exchange, thermal discomfort, and increased health risks. Across the four NV scenarios, stagnant airflow regions were consistently identified, particularly in Zones 2 and 3, as well as areas shielded from direct airflow pathways, such as room corners and sections distant from open windows. These areas exhibited low air speeds (below 0.1 m/s), resulting in localised heat accumulation and elevated RH, thus exacerbating discomfort and potentially prolonging the persistence of the airborne virus.

In Scenarios 1 and 2, representing summer conditions, dead zones were most pronounced in Zones 2 and 3, as well as areas within Zone 1 that were far from open windows. Limited air circulation in these regions led to PMV values exceeding 0.5 and PPD values exceeding 30%, indicating notable occupant dissatisfaction. Furthermore, insufficient airflow contributed to elevated RH levels exceeding 65%, increasing the likelihood of discomfort and reducing IAQ.

Scenario 3 also showed persistent dead zones in Zones 2 and 3, where air speeds ranged between 0 and 0.1 m/s, further contributing to elevated RH ($> 65\%$) and decreased occupant comfort. However, Zone 1 showed better airflow compared to previous scenarios, benefiting from improved ventilation due to window placement and external wind forces.

In contrast, Scenario 4 demonstrated improved air circulation in most of Zone 1, with acceptable air velocities (≥ 0.2 m/s). However, high airflow speeds (up to 0.4 m/s) were observed near open windows and parts of Zone 2. Although increased ventilation rates can improve IAQ, excessive airflow velocities pose a concern because they can facilitate the rapid dispersion of airborne contaminants. This aligns with the findings of [332], who highlight that higher air velocities can increase aerosol transmission, potentially exposing more occupants to airborne pathogens.

6.6.3 Impact of Air Velocity on Virus Dispersion

Air velocity plays a critical role in determining airborne particle transport, dispersion, and deposition, particularly in naturally ventilated environments where airflow is driven primarily by window openings, outdoor wind conditions, and internal convection currents. The CFD simulations of Scenario 4, which analysed aerosol dispersion from coughing and sneezing events, revealed that air velocity variations near open windows significantly influenced the movement of virus-laden particles within the office space.

During coughing events, the particles were expelled at an initial velocity of 11.8 m/s, following a forward-projected trajectory. Airflow near window openings, particularly in Window 1, facilitated rapid particle movement, increasing the risk of direct exposure to occupants seated along the airflow pathway.

The first infected individual, located near Window 1, experienced strong particle dispersion because the high local air velocity (>0.2 m/s) propelled the expelled aerosols through the workspace, increasing the risk of exposure of the occupant. However, the third and fourth infected individuals, located in Zones 2 and 3, also exhibited significant aerosol movement because the particles aligned with window-induced airflow patterns, which transported contaminants deeper into the space. In addition, the second infected individual, located farther from Window 1, experienced a reduced aerosol dispersion because the local air velocity in this area was lower. However, particles remained suspended longer, increasing the risk of localised exposure in low-ventilation zones. These findings highlight two major concerns:

- High air velocities near window openings accelerate aerosol dispersion, leading to widespread exposure among multiple occupants.
- Low-speed regions create stagnation zones, where aerosols linger longer, increasing localised inhalation risks.

Sneezing, which involves a much higher initial expulsion velocity (up to 70 m/s), showed more extensive and rapid dispersion compared to coughing. The simulation results demonstrated that the first infected individual's particles spread over 6 m, propelled by high window-induced air velocities. This extended reach increased the likelihood of particles being inhaled by multiple individuals farther from the source. However, the third and fourth infected individuals showed similar trends, where sneezed particles aligned with window-driven airflow patterns, leading to rapid transport into Zones 2 and 3. The second infected individual's particle dispersion exhibited a lower particle dispersion due to reduced airflow near the source, but the kinetic energy of the sneezed particles allowed them to spread widely, even in low-speed environments. These findings highlight the following:

- Sneezing events pose a significantly higher risk of dispersion because particles can spread across multiple zones in seconds, increasing potential exposure.
- High-velocity airflow near open windows further amplifies dispersion, creating long-range transmission pathways of airborne virus.

6.6.4 Impact of Relative Humidity on Comfort and Airborne Virus Stability

RH is a critical factor that influences both TC and the persistence of airborne pathogens, making it a key parameter in the management of indoor air quality. ASHRAE guidelines recommend maintaining indoor RH between 30% and 60% to optimise comfort and minimise potential health risks, while research suggests that an RH range of 40% to 60% is particularly effective in reducing viral stability and transmission risks [159, 260]. However, the findings of this study indicate that NV alone was insufficient to maintain RH within the recommended range, often resulting in excessive humidity levels in various scenarios.

In Scenario 4 (opening multiple windows), the unregulated influx of humid outdoor air caused the RH levels to exceed 80%, which exacerbated the discomfort related to moisture and further increased the risk of viral persistence. The high RH in these conditions compromised perceived air quality, making the environment feel stuffy and less ventilated, despite the presence of open windows.

Scenarios 1, 2, and 3 (summer conditions with single window ventilation) displayed moderate to high humidity levels, ranging between 65% and 75% in specific zones. This increase was primarily driven by the continuous intake of humid outdoor air and insufficient airflow regulation, which did not adequately disperse excess indoor moisture. In Zone 2, where stagnation of airflow was observed, HR levels remained consistently high, contributing to thermal discomfort and a prolonged risk of viral persistence. ASHRAE 55 notes that high RH, particularly in warm environments, can amplify the perception of heat stress, further exacerbating occupant discomfort.

6.6.5 Scenario Performance Evaluation

The performance of NV scenarios was assessed based on key indoor air quality parameters (IAQ) and TC, including air velocity, room temperature, RH, PMV and PPD. These results were evaluated against the ASHRAE 55, ISO 7730, and EN 16798 standards, which provide guidelines for maintaining acceptable TC and air quality. Comparative analysis of different scenarios provides insight into the effectiveness of NV in maintaining a comfortable and healthy indoor environment, while also highlighting areas where performance was suboptimal.

Scenario 1 simulated summer conditions with a single window open, allowing moderate thermal regulation. The room temperature remained between 20 °C and 22 °C, which is in good agreement with the ASHRAE comfort guidelines. The air velocity ranged from 0 to 0.2 m/s, suggesting that while there was some ventilation, airflow remained weak in certain areas. Zones 2 and 3, in particular, experienced lower airflow rates, leading to localised thermal imbalances and stagnation zones.

Relative humidity levels were elevated (65% to 70%), which, while not extreme, still exceeded the upper comfort threshold of ASHRAE of 60%, raising concerns about moisture retention and viral persistence. PMV values ranged from 0 to 0.8, indicating mildly warm conditions, with PPD levels around 10%, which means that most of the residents were satisfied with the indoor environment. However, the persistence of humidity and stagnant airflow in Zones 2 and 3 suggests that additional measures, such as optimised window placement or additional ventilation, would be necessary to improve air circulation and humidity control.

Scenario 2 maintained room temperatures between 20 °C and 23 °C, which is within the recommended range of ASHRAE. However, TC varied between different zones. Zone 1 exhibited optimal ventilation, with PMV values around 0 and PPD levels at 10%, indicating that most individuals were comfortable.

In contrast, Zones 2 and 3 experienced discomfort due to poor airflow and slightly higher temperatures. PMV values exceeded 0.5 in these zones and PPD levels exceeded 20%, suggesting increased occupant dissatisfaction. The air velocity in several areas remained below 0.1 m/s, which exacerbated stagnation and poor air mixing. Furthermore, RH levels persisted at 65% to 70%, which reinforces concerns about airborne virus longevity and overall IAQ. Improving ventilation distribution through window adjustments or mechanical airflow enhancements could help to mitigate localised comfort issues and enhance air circulation in under-ventilated zones.

Scenario 3 followed a similar pattern to Scenario 2, with Zones 2 and 3 experiencing discomfort due to insufficient air circulation. The air velocity across these zones was low (below 0.1 m/s in several locations), which limited effective ventilation and cooling.

Room temperatures remained within 20 °C and 23 °C, in line with ASHRAE recommendations, but RH levels continued to exceed 65%, raising concerns about airborne virus transmission and occupant comfort. Zone 1 maintained acceptable TC, with PMV values close to 0 and PPD levels at 10%, indicating that most of the occupants in this zone were comfortable. However, in Zones 2 and 3, the

PMV values exceeded 0.5, with PPD exceeding 20%, suggesting that significant portions of the occupants were dissatisfied.

Although Scenario 3 slightly improved airflow over previous cases, the persistence of humidity and stagnant airflow highlights the need for better ventilation management strategies, such as improved window configurations or hybrid ventilation systems.

Scenario 4 maximised NV by opening three windows, significantly improving air exchange. This approach resulted in higher air velocities (exceeding 0.2 m/s), with some areas reaching 0.4 m/s. Although this improved overall ventilation efficiency and particle dilution, it also introduced localised discomfort due to excessive cooling.

The room temperature was well regulated in Zones 1 and 3 (20 °C to 23 °C), according to the comfort standards of the ASHRAE. However, Zone 2 experienced temperature drops below 18°C, leading to cold stress and discomfort in the occupants. Relative humidity levels remained above 65%, consistent with previous scenarios, reinforcing the limitations of NV in controlling moisture levels.

TC analysis indicated that PMV values remained within an acceptable range (0.4) in Zones 1 and 3, with PPD around 10%. However, in Zone 2, PMV values dropped below -1, resulting in PPD levels exceeding 50%, highlighting a significant dissatisfaction due to excessive cooling and exposure to draught.

Although Scenario 4 provided the most effective air exchange, it demonstrated the risks associated with over-ventilation, where excessive air velocity increased aerosol dispersion and created thermal discomfort. This highlights the need for better airflow regulation, window positioning adjustments, and possible integration with mechanical systems to balance ventilation efficiency and TC.

Scenario	Air Velocity	Temperature	RH	PMV	PPD
1	0 - 0.2 m/s	20 °C - 24 °C	> 75%	0 to 1.2	> 30%
2	0.02 - 0.2 m/s	20 °C - 24 °C	> 70%	0 - > 1	< 20% - > 20%
3	0.02 - 0.35 m/s	20 °C - 22 °C	nearly 70%	-1.6 - > 1 (Zones 2 and 3)	PPD > 20%
4	0.2 - 0.4 m/s	18.5 °C - 23 °C	> 80%	-2.5 - 1	10% - > 50% (Zone 2)

Table 6.4: Comparative summary of scenario performance

6.6.6 Comparison of Natural Ventilation Against Air Conditioning

NV and AC represent two distinct approaches to maintaining IAQ and TC. NV relies on outdoor air movement and pressure differentials to drive airflow, while AC uses controlled air circulation through fans, ducts, and HVAC systems. The findings of this study highlight the strengths and limitations of each system in terms of air velocity, temperature regulation, humidity control, and overall TC.

One of the primary differences between the two ventilation strategies is air distribution. NV demonstrated inconsistent and uneven airflow, leading to stagnant air zones, particularly in areas shielded from direct airflow pathways, such as Zones 2 and 3. In these regions, the air velocity frequently fell below 0.1 m/s, which reduced the effectiveness of ventilation and contributed to localised thermal discomfort. AC, on the other hand, maintained a more uniform air distribution, with air velocities ranging between 0.1 and 0.25 m/s. However, despite its consistency, the AC also exhibited stagnation in airflow in corners and behind furniture, indicating that neither system was completely free of airflow deficiencies. In addition, NV was highly dependent on external weather conditions, making its performance unpredictable. In some scenarios, high-velocity airflow near open windows exceeded 0.4 m/s, leading to localised discomfort and an increased risk of viral dispersion. In contrast, AC provided more controlled and predictable airflow, but primarily recirculated indoor air without introducing fresh outdoor air, which could contribute to pollutant buildup and increased infection risks.

Temperature regulation also varied significantly between the two systems. NV produced uneven thermal conditions, with areas near windows experiencing cooling or heating effects, while enclosed regions retained heat due to poor air circulation. The room temperatures in NV scenarios ranged between 18.5 °C and 23 °C, depending on the outside temperature, which is not consistent with the ASHRAE comfort recommendations in some scenarios. However, AC provided more stable temperature control, maintaining indoor temperatures within 22 °C to 25 °C in most zones. However, cold air pockets formed in some areas due to uneven air mixing, making occupants uncomfortable near the air vents. TC analysis also indicated that NV often failed to maintain PMV within the recommended range of ASHRAE of -0.5 to +0.5, particularly in stagnant zones where PMV values exceeded 0.5. In contrast, AC generally maintained the PMV within the optimal range, but occasionally caused over-cooling in specific locations.

Humidity control was another area where natural and AC exhibited distinct performance characteristics. NV was unable to effectively regulate indoor RH because it was entirely dependent on external humidity conditions. As a result, RH levels frequently exceeded 65%, particularly in humid outdoor conditions, increasing the stability of the airborne virus and the risk of mould growth. AC partially controlled the humidity, but it was still unable to maintain the RH consistently within the optimal range of 30% to 60%, as recommended by ASHRAE. Some areas with AC exhibited an RH above 65%, highlighting the need for additional measures of dehumidification. Furthermore, the reliance of the AC on recirculated air without sufficient filtration posed a risk of pollutant accumulation, while NV facilitated fresh air exchange but suffered from stagnation in certain zones, reducing its effectiveness in contaminant removal.

In general, AC provided more consistent airflow and temperature regulation, but lacked fresh air exchange, which is essential to maintain good indoor air quality. While NV was effective in facilitating fresh air intake, it suffered from uneven airflow distribution, leading to thermal imbalances and humidity fluctuations. Both systems exhibited limitations that affected occupant comfort and IAQ, suggesting that a hybrid approach combining natural and AC (referred to as mixed-mode ventilation) could address these shortcomings more effectively.

6.6.7 Recommendations for Optimising Natural Ventilation Performance

The findings from the CFD simulations and discussion sections (see section 6.5 and section 6.6) demonstrate that while natural ventilation (NV) offers a passive and energy-efficient means of improving indoor air quality (IAQ) and thermal comfort (TC), its effectiveness is highly dependent on external climatic conditions, window configurations, and occupant behaviour. To enhance the reliability and performance of NV in office environments, several key recommendations are proposed:

- Strategic Window Placement and Operation: The performance of NV is strongly influenced by the location, size, and operability of windows. As demonstrated in Scenario 4 (section 6.5.4.1), cross-ventilation (CV) significantly improved airflow distribution. Therefore, buildings should incorporate multiple, strategically placed openings to enable effective cross-ventilation. Adjustable configurations, such as operable louvres or top-hung windows, can help regulate air intake based on real-time wind conditions, preventing over-ventilation and reducing draught discomfort (see section 6.6.5).

- Addressing Dead Zones: Stagnant airflow zones—particularly identified in Zones 2 and 3 of Scenarios 1, 2, and 3 (see section 6.5.1.1, section 6.5.2.1, section 6.5.3.1, and section 6.6.2 which led to poor ventilation and localised pollutant accumulation. To mitigate this, passive elements like chimney stacks or wind catchers, along with mechanical aids such as ceiling fans or small exhaust units, can promote air mixing in under-ventilated areas. Integrating NV with mechanical support (mixed-mode ventilation) is recommended where full natural ventilation is insufficient.

- Managing Relative Humidity (RH): Elevated levels of RH, often exceeding 75% in Scenarios 4 (see section 6.5.4.2) can promote viral stability and discomfort. It is recommended to incorporate dehumidification strategies or use ventilation controls that modulate air intake during high-humidity periods. In humid climates or seasons, combining NV with mechanical dehumidification systems offers a more reliable solution.

- Controlling Air Velocity and Infection Risk: High air velocities near open windows (e.g., Scenario 4 in section 6.5.4.4) increased aerosol dispersion distances, raising the risk of airborne transmission. To reduce this risk, airflow should be maintained within ASHRAE's recommended indoor velocity range of 0.2 m/s (see section 6.6.3). This can be achieved by limiting window opening angles or automating ventilation through actuators linked to real-time CO2 or particle concentration sensors.

- Enhancing Occupant Awareness and Behaviour: Occupant interaction plays a critical role in NV effectiveness. Providing users with simple visual guidance (e.g., window position indicators or IAQ monitors) and instructions based on weather or room conditions can encourage optimal use of operable windows. As discussed in section 6.6.6, hybrid strategies can complement occupant behaviour to maintain a consistent indoor environment throughout the day.

By addressing these factors, window design, airflow optimisation, humidity control, velocity management, and occupant engagement, NV systems can be significantly enhanced. These recommendations aim to support architects, engineers, and building managers in designing and operating natural ventilation strategies that are resilient, adaptive, and effective under a range of environmental and occupancy conditions.

6.7 Conclusion

This chapter has investigated the performance of NV in improving IAQ, regulating TC, and mitigating the risk of airborne virus transmission in an office environment. Using CFD simulations, five scenarios were analysed under varying environmental conditions and ventilation configurations. The findings provide important information on the effectiveness of NV, as well as the associated challenges and optimisation strategies required to achieve better indoor environmental quality.

The effectiveness of NV was largely dependent on the placement of windows, external airflow conditions, and pressure differentials. CV, particularly in Scenario 4, provided the most efficient airflow distribution, reducing stagnant air regions and improving ventilation performance. However, this scenario also introduced challenges because excessive air velocities near open windows led to over-cooling and an increased risk of respiratory aerosol dispersion. In contrast, Scenario 1,2 and 3, demonstrated inadequate ventilation, resulting in poor air exchange and stagnation in multiple zones.

This study also assessed the ability of NV to maintain TC in different scenarios. The results showed that Scenario 1, 2 and 3, Zone 1 exhibited optimal TC, with PMV values between 0 and 0.5 and PPD levels below 10%, aligning with the ASHRAE TC standards. However, Zones 2 and 3 in these scenarios experienced slightly warm conditions, where PMV values exceeded 0.5 and PPD levels exceeded 20%, primarily due to limited airflow and insufficient CV. Scenario 4, which used multiple window openings, introduced localised over-cooling, particularly in areas directly exposed to airflow, where PMV values decreased below -1, leading to PPD values exceeding 50% in certain areas.

The influence of air velocity on virus dispersion was another key aspect that was analysed in this study. Higher air velocities (> 0.2 m/s) near windows significantly increased the dispersion range of airborne particles, posing a risk of cross-contamination among occupants. In Scenario 4, respiratory particles expelled by infected individuals positioned near open windows were rapidly transported across the room, reaching adjacent zones and affecting multiple occupants. Conversely, low air velocity regions (<0.1 m/s), particularly in Zones 2 and 3, allowed particles to remain suspended for longer durations, which increased the risk of prolonged exposure.

RH was another critical factor affecting both occupant comfort and airborne virus stability. In most scenarios, RH exceeded the ASHRAE-recommended range of 30% to 60%, with levels frequently surpassing 65%. Scenario 5 recorded RH levels above 80%, which can be attributed to the humid outdoor air influx through multiple open windows. These findings highlight the importance of integrating humidity control strategies to maintain acceptable indoor RH levels and minimize health risks.

The analysis also identified significant stagnant air regions (dead zones) in Zones 2 and 3 in multiple scenarios, particularly in Scenarios 1, 2, and 3. These areas exhibited low air speeds, leading to localised temperature buildup, poor ventilation, and increased pollutant accumulation. Dead zones also contributed to higher exposure risks due to prolonged aerosol suspension. Addressing these stagnant regions requires strategic airflow management, and integration of AC with NV may be necessary to ensure adequate circulation.

Several key recommendations have been identified to optimise the performance of NVs. First, regulating window opening sizes can help to control airflow intensity, preventing excessive ventilation that may lead to over-cooling or rapid aerosol dispersion. Introducing adjustable dampers or controlled ventilation schedules can further enhance ventilation efficiency. Second, to integrate mixed-mode ventilation, combining NV with AC can help to mitigate the impact of dead zones and improve air circulation in poorly ventilated areas. Implementing ceiling fans or air circulation systems in stagnant regions can further reduce pollutant accumulation and enhance TC. Third, maintaining RH levels below 60% through dehumidification strategies is essential to improve IAQ and reduce the stability of airborne viruses. Furthermore, ensuring that air velocities remain within the recommended ASHRAE threshold of 0.2 m/s can balance adequate ventilation while minimising excessive aerosol dispersion.

In direct response to Research Question 3 (RQ3), the results show that NV when effectively configured can significantly improve airflow distribution, enhance thermal comfort, and reduce airborne infection risks in indoor environments. However, without careful control, it may also introduce challenges such as uneven airflow, humidity excess, and uncontrolled particle spread.

Regarding Research Question 4 (RQ4), this chapter demonstrates how NV strategies can be adapted under different environmental conditions to optimise indoor environmental quality. Specifically, cross-ventilation with moderated airflow and supplemental mechanical support emerges as the most balanced and effective configuration.

This chapter provides several key contributions to the field of indoor environmental quality and ventilation design. First, it presents a detailed CFD-based assessment of natural ventilation (NV) strategies under varying environmental conditions, providing insight into the dynamics of airflow, thermal comfort, and pollutant dispersion in office environments. Second, it highlights the limitations of conventional NV configurations, such as the presence of stagnant zones, overcooling, and uncontrolled aerosol transport, while demonstrating the effectiveness of cross ventilation as a superior strategy. Third, the chapter introduces evidence-based design recommendations for optimising NV performance, including mixed-mode ventilation, humidity control, and strategic airflow regulation. These findings advance our current understanding of the role of NV in improving IAQ, mitigating infection risk and improving thermal comfort, and they serve as a foundation for future development of adaptive and sustainable ventilation solutions in modern buildings.

In conclusion, this study has shown that when NV is optimised it can significantly improve indoor air quality, improve TC, and contribute to infection control. However, challenges such as uneven airflow distribution, excessive humidity levels, and the uncontrolled spread of airborne contaminants must be addressed to fully harness the benefits of NV. The findings emphasise the need for an integrated ventilation approach, in which NV is supplemented by adaptive mechanical strategies to ensure a healthier and more sustainable indoor environment. Future research should focus on real-time ventilation monitoring and dynamic airflow control systems, allowing data-driven optimisation of NV strategies. Furthermore, hybrid ventilation models that incorporate intelligent mechanical controls can further enhance the performance of NV, ensuring its viability as a long-term solution to maintain indoor environmental quality.

Chapter 7

Mixed Ventilation

7.1 Introduction

This chapter directly addresses **Research Question 3 (RQ3) and Research Question 4 (RQ4)**. Building upon the findings of Chapter 5 (which identified limitations in fully air-conditioned systems, particularly in terms of dead zones and uneven airflow) and Chapter 6 (which demonstrated that fully natural ventilation, while beneficial for fresh air exchange, can lead to overcooling, inconsistent airflow, high RH, and increased infection risk), this chapter investigates mixed-mode ventilation as an integrated solution to overcome these challenges.

Mixed-mode ventilation, commonly referred to as hybrid ventilation, integrates NV and AC strategies to optimise IAQ, TC, and reduce virus transmission. Unlike full AC systems, which rely on continuous energy consumption for air circulation and temperature control, mixed ventilation leverages natural airflow (e.g., operable windows) when outdoor conditions are favourable, while activating AC systems as needed to maintain stable indoor environmental conditions. This dynamic approach aims to reduce HVAC energy costs, while ensuring sufficient air exchange and occupant comfort [312]. The choice of ventilation strategy significantly influences thermal regulation, air distribution, and pollutant removal efficiency. NV is widely recognised for its ability to improve IAQ and reduce overheating risks, particularly in buildings designed with efficient cross ventilation pathways [333, 334]. However, it remains highly dependent on external weather conditions, outdoor air quality, and occupant behaviour, making it unreliable for consistent IAQ control. In contrast, AC offers precise control over temperature and air circulation, but requires higher energy consumption and may result in uneven air distribution [334]. Consequently, an integrated hybrid ventilation approach presents a potential solution, combining the advantages of both strategies while mitigating their individual limitations.

A key limitation identified in the baseline study (Chapter 5) was that a full AC system alone was insufficient to optimise IAQ in all zones. Although AC maintained air exchange, it resulted in stagnation zones and uneven airflow distribution, ultimately compromising TC. As a potential alternative, Chapter 6 investigated fully NV scenarios. However, the findings indicated that NV alone was ineffective in maintaining stable indoor temperatures, leading to thermal discomfort and increased aerosol dispersion, increasing the risk of airborne virus transmission. Given these limitations, a hybrid ventilation approach in which air conditioning and NV is strategically combined is hypothesised to overcome these challenges. By balancing fresh air intake and AC airflow control, mixed ventilation has the potential to improve IAQ, TC, and virus containment more effectively than fully AC or fully natural systems. Several studies have demonstrated the effectiveness of hybrid ventilation in optimising IAQ and TC. The research by [335] emphasised the importance of airflow regulation to reduce airborne contaminant accumulation. Their findings suggest that adjustable hybrid ventilation systems can significantly mitigate aerosol concentrations, thereby improving airborne infection control. Similarly, [336] found that AC, when combined with partial window openings (30%), reduced the risk of infection transmission by 58% to 70% compared to fully enclosed spaces.

7.1.1 Chapter Objectives

The primary objective of this chapter is to evaluate the performance of mixed ventilation to maintain optimal airflow patterns, TC, and control of airborne infections in an office environment. The study aims to evaluate the effectiveness of hybrid ventilation strategies using CFD simulations. Specifically, this chapter seeks to:

- Analyse the airflow distribution in different mixed ventilation scenarios and its impact on air circulation.
- Evaluate the variations in temperature and RH in mixed ventilation strategies.
- Assess occupant TC using the PMV and PPD indices.
- Examine aerosol dispersion patterns during coughing and sneezing events to understand the risk of airborne virus transmission.
- Compare the performance of mixed ventilation with the ASHRAE 55, EN 16798, and ISO 7730 standards for TC to ensure that the system meets the recommended ventilation effectiveness criteria.
- Identify the most effective mixed-ventilation strategy that improves IAQ and reduces thermal discomfort.

7.2 Methodology

This study employs a CFD simulation approach to evaluate the performance of mixed ventilation in an open-plan office environment. This methodology follows a structured framework, beginning with the identification of key parameters and solver settings, followed by the development of a computational model that incorporates geometry, meshing, and boundary conditions. The CFD simulation assesses IAQ, TC, and aerosol dispersion, providing insight into the effectiveness of mixed ventilation strategies under different seasonal conditions. The results are analysed for airflow patterns, temperature regulation, RH, TC indices of the occupants (PMV and PPD), and risks of transmission of airborne viruses. Finally, recommendations are derived based on the findings to optimise the performance of mixed ventilation. The general research framework is illustrated in Figure 7.1, summarising the step-by-step process undertaken in the simulations.

Figure 7.1: Overview of the methodology for mixed ventilation simulations

7.3 Scenario Development

This chapter evaluates three different mixed ventilation scenarios to evaluate system performance under different seasonal conditions and ventilation strategies, as summarised in Table 7.1. Each scenario evaluates airflow distribution, temperature control, humidity levels, and human TC metrics.

Scenario No.	Season	Natural Configuration	Environmental Conditions	Mixed Configuration	Environmental Conditions
1	Winter	Single Window Open (Window 4) in Zone 1	T = 4 °C, V = 3 m/s, RH = 0.004	Single AC operates in Zone 1 (upper right corner)	AC = 19 °C. H2O = 0.0177
2	Winter	Single Window Open (Window 4) in Zone 1	T = 13 °C, V = 3 m/s, RH = 0.004	Single AC operates in Zone 1 (upper right corner)	AC = 19 °C, H2O = 0.006
3	Summer	Single Window Open (Window 6) in Zone 1	T = 19 °C, V = 3 m/s, RH = 0.004	Single AC operates in Zone 2 (upper left corner)	AC = 13 °C, H2O= 0.0083

Table 7.1: Mixed ventilation scenarios and their environmental conditions.

7.4 Boundary Conditions

The simulation was conducted under steady-state conditions to capture the combined effects of NV and AC on air distribution, thermal regulation, and respiratory particle dispersion. The mixed ventilation system consisted of an open window that allowed fresh outdoor air to be exchanged and a ceiling mounted AC unit to maintain indoor temperature stability. This setup represents a realistic mixed-mode ventilation strategy, where natural air flow complements AC conditioning, improving TC, air quality, and helping to reduce virus transmission.

The NV component was modelled using a boundary condition of velocity entry in the open window to simulate the entry of outdoor air, with the air temperature adjusted according to seasonal conditions. The inlet temperature was set to 4 °C for winter (Scenario 1), 13 °C for mild winter (Scenario 2), and 19 °C for summer (Scenario 3). The velocity of the outdoor air was maintained at 3 m/s, ensuring adequate fresh air intake and cross ventilation within the office space.

The AC component was represented by an AC unit that supplied conditioned air, with temperature settings adjusted based on seasonal requirements. In winter scenarios, the AC supplied air at 19°C, ensuring a warm and stable indoor environment, while in summer scenarios the AC operated at 13°C, providing cooling effects to maintain occupant comfort. The combined operation of NV and AC facilitated continuous fresh air exchange while stabilising indoor temperatures, preventing overheating or excessive cooling in occupied zones.

To maintain proper airflow balance, the air outlet was set as a pressure outlet, ensuring continuous air discharge without backflow or pressure build-up. This boundary condition facilitated steady indoor air circulation, preventing stagnant airflow pockets that could reduce the effectiveness of ventilation. The interaction between NV and AC components was analysed to determine how airflow distribution, contaminant removal, and TC levels were influenced by the hybrid system.

To comprehensively assess mixed ventilation performance, this study considered 10 different simulation cases, as outlined in Table 7.2. The first set of cases (cases 1, 3, and 5) assessed ventilation efficiency by analysing airflow, temperature, and the RH distribution when a single window was open under different seasonal conditions. Cases 2, 4, and 6 examined the comfort of the occupant in mixed-mode ventilation scenarios. The final set of cases (cases 7 to 10) introduced an infected occupant in different workstation positions (A, B, C, and D) to assess how airborne particles dispersed under combined NV and AC. This analysis provided insight into how airflow direction, ventilation effectiveness, and spatial configurations impacted IAQ and infection risks.

Case No.	Scenario	Infected Source	Notes
1	Scenario 1	None	Assessment of ventilation performance through one window at T= 4 °C, and AC at T= 19 °C.
2	Scenario 1	None	Assessment of thermal comfort.
3	Scenario 2	None	Assessment of ventilation performance through one window at T= 13 °C, and AC at T= 19 °C.
4	Scenario 2	None	Assessment of thermal comfort.
5	Scenario 3	None	Assessment of ventilation performance through one window at T= 19 °C, and AC at T= 13 °C.
6	Scenario 3	None	Assessment of thermal comfort.
7	Scenario 3	A	Assessment of infection risk.
8	Scenario 3	B	Assessment of infection risk.
9	Scenario 3	C	Assessment of infection risk.
10	Scenario 3	D	Assessment of infection risk.

Table 7.2: Overview of simulation cases during the MV.

7.5 Results

This section presents the findings of three different mixed ventilation scenarios, each designed to evaluate the interaction between NV and AC (MV) in the regulation of IAQ, TC, and airflow distribution. This study specifically examines the influence of outdoor air infiltration through open windows and the impact of localised AC systems, focussing on key parameters such as air velocity patterns, temperature variations, RH and TC indices, including PMV and PPD.

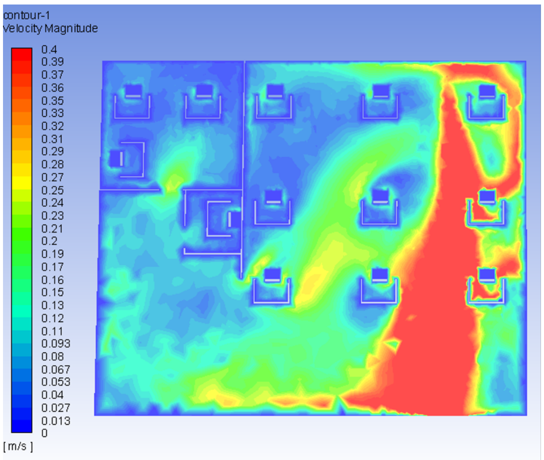
7.5.1 Scenario 1

7.5.1.1 Air Velocity Pattern

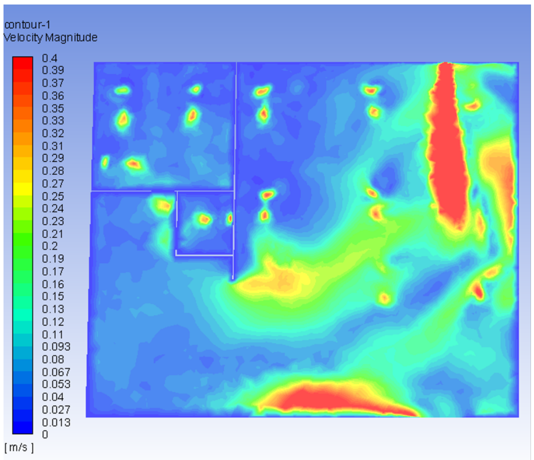
The air velocity distribution for Scenario 1, representing a mixed ventilation system during winter conditions, highlights the interaction between AC and NV through an open window (Window 4).

Figure 7.2 illustrates the overall velocity distribution in the office space, revealing an unstable airflow pattern, particularly in Zone 1, where velocity values fluctuate between 0.1 m/s and 0.4 m/s. The highest velocities are concentrated near the window and along the airflow trajectory, while areas near the occupants in the central sections of Zone 2 and Zone 3 exhibit reduced airflow, with velocities as low as 0.02 m/s to 0.1 m/s. This reduction in velocity can be attributed to the limited direct airflow pathways available in these areas, resulting in lower air exchange rates compared to Zone 1.

In general, the air velocity distribution in Scenario 1 suggests that the combination of AC and NV contributes to effective airflow circulation in Zone 1, while airflow in Zones 2 and 3 remains relatively stagnant due to the absence of direct ventilation openings. This highlights the need for additional ventilation strategies to improve airflow uniformity and mitigate possible air stagnation in enclosed zones.



(a) z = 1 m



(b) z = 2 m

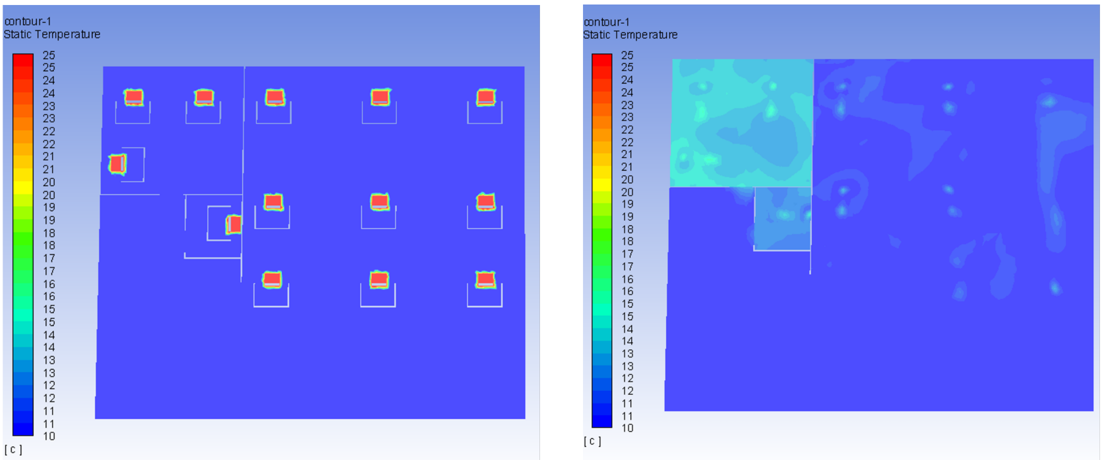
Figure 7.2: Air velocity contour in z direction during Scenario 1 of mixed ventilation.

7.5.1.2 Room Temperature and Relative Humidity

The room temperature distribution in Scenario 1 illustrates the thermal interactions between NV, introduced through an open window, and AC from a localised AC system. Figures 7.3 depict the spatial temperature variations in the three office zones, highlighting the impact of airflow dynamics and thermal stratification.

The results suggest that the overall temperature remains relatively low, indicating that AC has a limited impact due to the dominant cooling effect of outdoor air. The cold air introduced through NV overpowers the warming effect of AC heating, rendering the AC system ineffective in maintaining a balanced indoor temperature.

The analysis of the temperature distribution in Scenario 1 highlights that mixed ventilation is not effective in maintaining TC under extreme winter conditions. The dominance of cold outdoor air results in an excessively cold indoor environment, which reduces the efficiency of the AC system. These findings emphasise that keeping windows open in very cold conditions is not a suitable ventilation strategy because it leads to significant heat loss and discomfort for the occupants. Alternative solutions, such as regulated window openings, controlled ventilation rates, or additional heating, should be considered to maintain an optimal indoor climate.



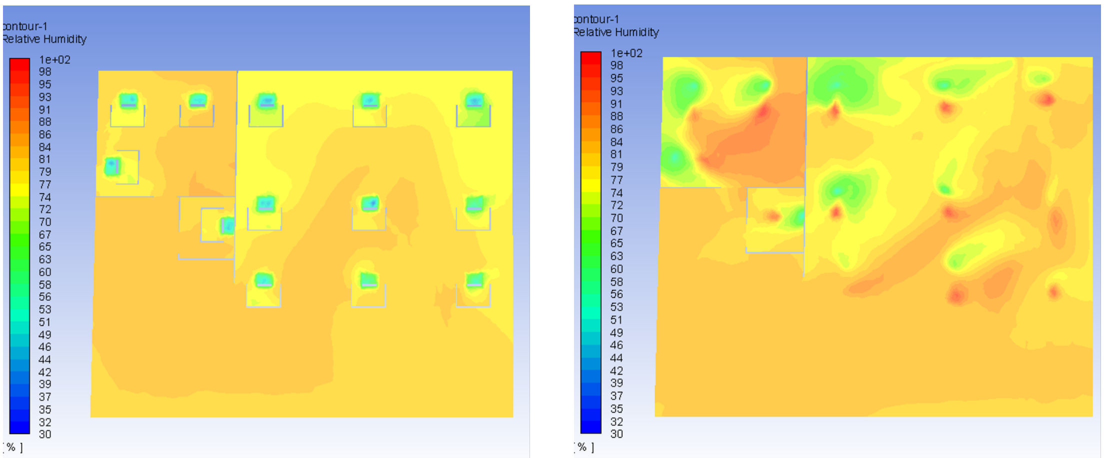
(a) z = 1 m (b) z = 2 m

Figure 7.3: Temperature contour in z direction during Scenario 1 of mixed ventilation.

The distribution of RH in Scenario 1 illustrates the combined effects of NV (introduced through the open window) and AC (provided by the AC system).

Figures 7.4 depict the spatial variations in RH in the three office zones, highlighting the influence of airflow patterns and ventilation sources.

The results indicate that the RH levels near the occupants who are farther from the open window and the airflow input range between 60% and 70%, providing relatively moderate humidity conditions. However, the rest of Zone 1, as well as Zones 2 and 3, exhibit significantly higher levels of RH exceeding 79%, indicating that moisture accumulation is more prominent in these areas.



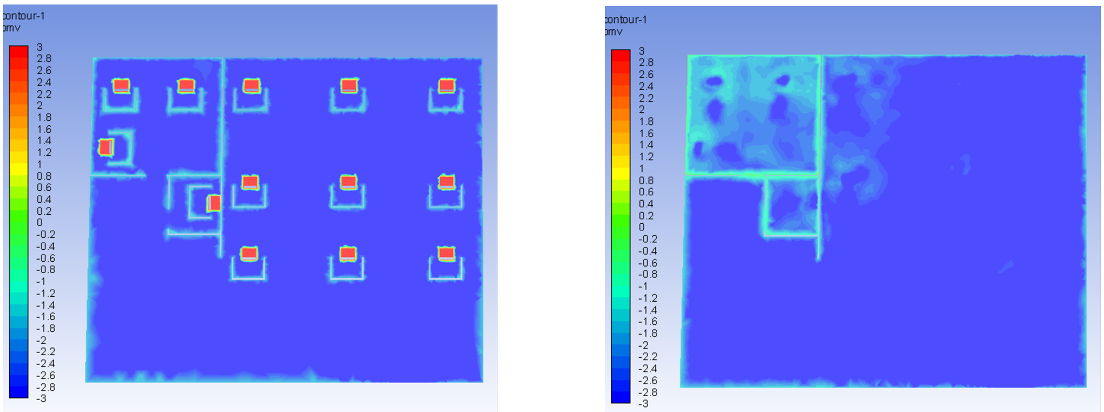
(a) z = 1 m (b) z = 2 m

Figure 7.4: RH contour in z direction during Scenario 1 of mixed ventilation

7.5.1.3 Predicted Mean Vote and Predicted Percentage of Dissatisfied

The PMV index is used to evaluate TC by assessing the combined influence of air temperature, humidity, air velocity, metabolic rate, and clothing insulation.

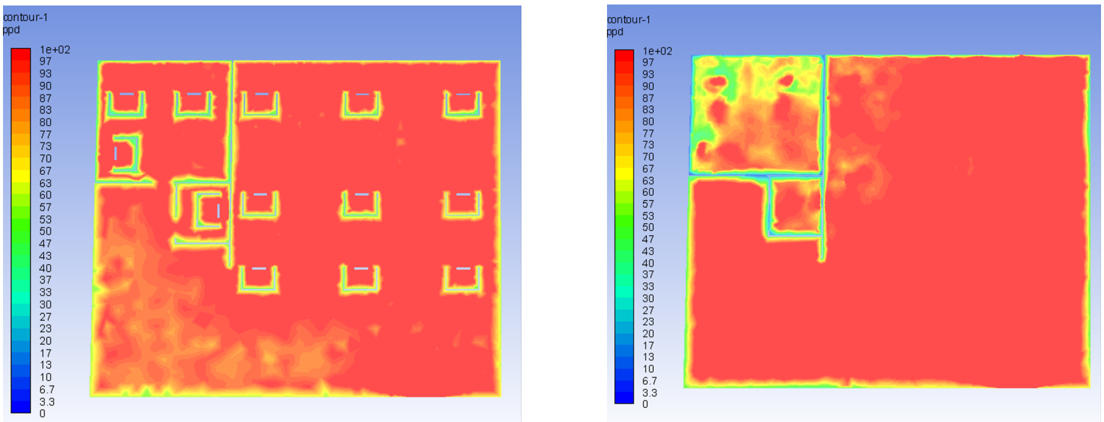
Figures 7.5 present the spatial distribution of PMV values across the three monitored office zones. The simulation results reveal a significant variation in thermal comfort levels among the different areas. Specifically, Zone 1 is characterised by PMV values of -2 or lower across most regions, indicating that occupants in this zone are likely to feel cold and experience notable thermal discomfort. In contrast, Zones 2 and 3 display slightly better thermal conditions, with PMV values predominantly ranging between -1 and -2. While this range suggests a milder level of discomfort compared to Zone 1, it still falls outside the acceptable thermal comfort range defined by international standards such as ASHRAE 55 and ISO 7730. Overall, these findings confirm that none of the zones provide thermally comfortable conditions, emphasising the need for improved ventilation or heating strategies to enhance occupant comfort.



(a) z = 1 m (b) z = 2 m

Figure 7.5: PMV contour in z direction during Scenario 1 of mixed ventilation

The PPD index quantifies occupant discomfort levels based on deviations from optimal TC conditions. Figures 7.6 illustrate the distribution of PPD in the three office zones, highlighting the impact of NV and AC on thermal conditions. The results indicate that most areas in all three zones exhibit extremely high PPD values, exceeding 90%. Zone 2 shows a slightly lower PPD of approximately 50% in some areas, but this still falls outside the comfort range.



(a) z = 1 m (b) z = 2 m

Figure 7.6: PPD contour in z direction during Scenario 1 of mixed ventilation

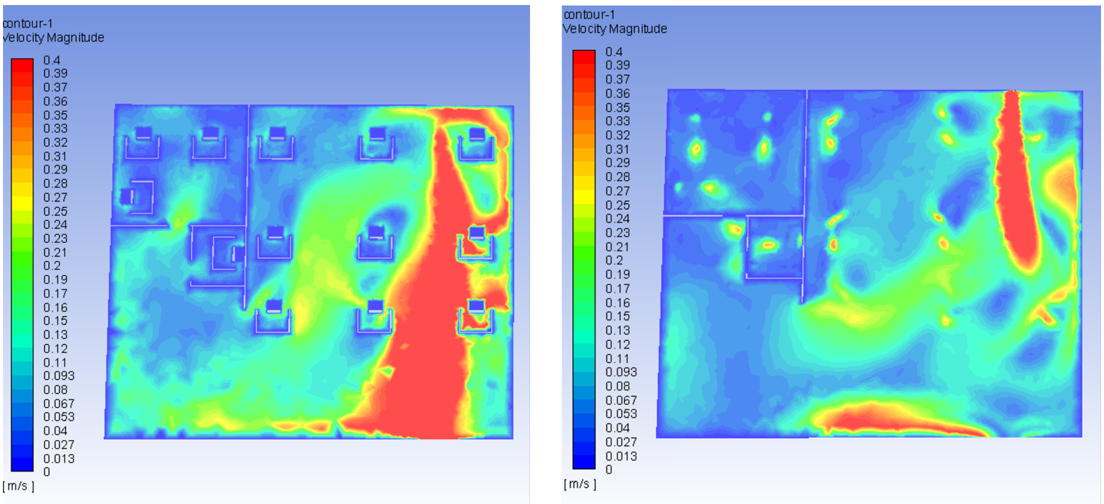
7.5.2 Scenario 2

7.5.2.1 Air Velocity Pattern

Scenario 2 follows a ventilation strategy similar to Scenario 1, but incorporates a higher outdoor air temperature (13 °C) and an increased absolute humidity ratio (0.006 kg/kg).

Figures 7.7 provides an overview of the air velocity distribution throughout the office layout.

The general velocity analysis for Scenario 2 reveals a marginal improvement in airflow homogeneity compared to Scenario 1, particularly within Zone 1, where external ventilation provides consistent air movement. However, Zones 2 and 3 continue to experience restricted airflow, reinforcing the conclusion that additional ventilation sources or airflow redistribution strategies may be required to improve circulation efficiency in enclosed areas.



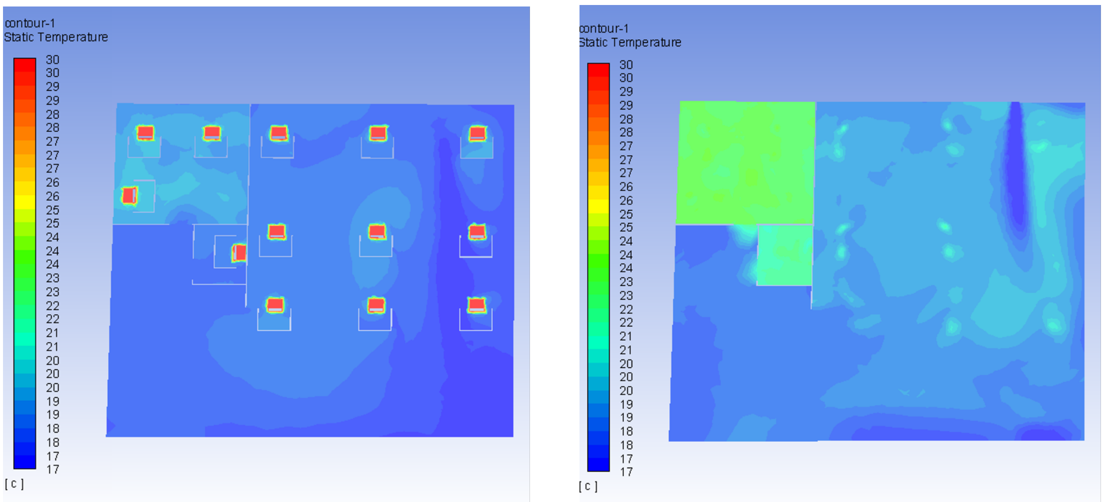
(a) z = 1 m (b) z = 2 m

Figure 7.7: Air velocity contour in z direction during Scenario 2 of mixed ventilation.

7.5.2.2 Room Temperature and Relative Humidity

The temperature distribution in Scenario 2 highlights the interaction between NV from the open window and AC from the localised AC system. Figure 7.8 provides an overview of the temperature distribution throughout the office layout.

The results suggest that the AC system is more effective in Scenario 2 compared to Scenario 1 because slightly warmer outdoor air (13 °C) does not create excessive cooling. The temperature distribution analysis for Scenario 2 indicates that mixed ventilation achieves moderate TC under winter conditions, with a more balanced indoor temperature compared to Scenario 1. Although NV still introduces cool air, the AC system compensates more effectively in this scenario, reducing extreme temperature variations. These findings highlight the importance of the temperature of the outdoor air in determining the effectiveness of mixed ventilation strategies, highlighting that slightly warmer outdoor conditions allow better temperature regulation without excessive cooling.

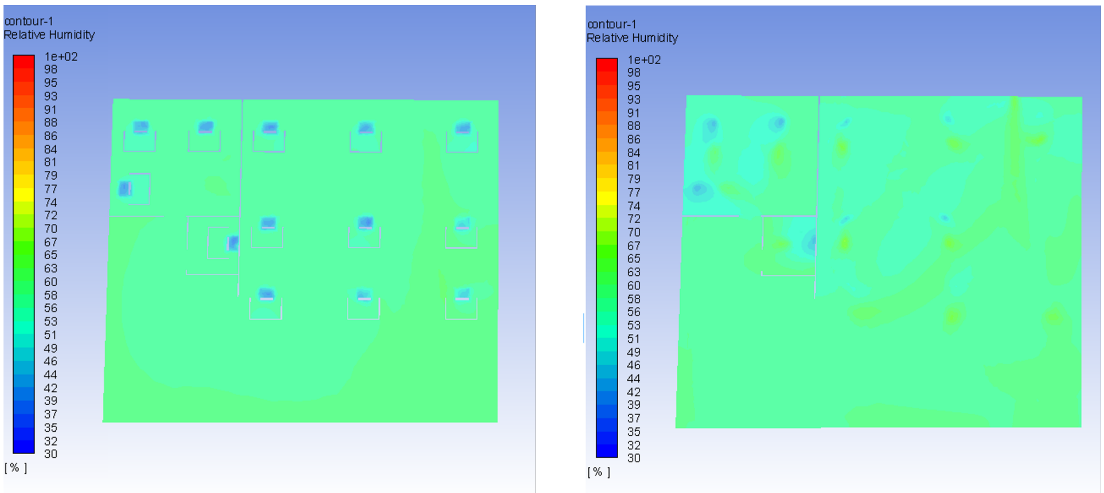


(a) z = 1 m (b) z = 2 m

Figure 7.8: Temperature contour in z direction during Scenario 2 of mixed ventilation.

The distribution of RH in Scenario 2 illustrates the combined effects of NV (introduced through an open window) and AC (provided by the AC system). Figure 7.9 provides a broader perspective of the RH distribution.

The results indicate that most areas in Zones 1, 2, and 3 experience levels of RH above 65%, with some areas in Zone 2 exhibiting lower RH values around 50%. This suggests that while NV and AC contribute to the variation in moisture in different areas, overall RH remains close to the acceptable range for indoor comfort.



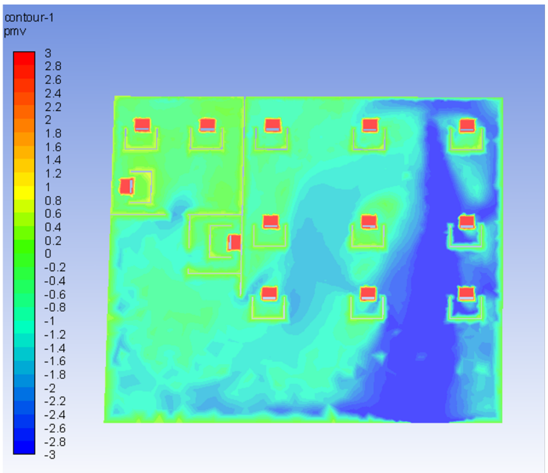
(a) z = 1 m (b) z = 2 m

Figure 7.9: RH contour in z direction during Scenario 2 of mixed ventilation

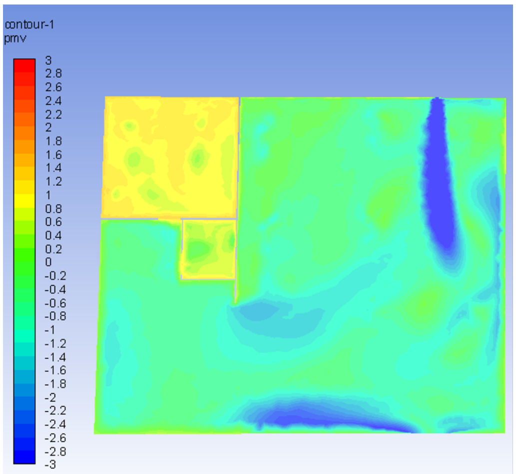
7.5.2.3 Predicted Mean Vote and Predicted Percentage of Dissatisfied

The PMV index is used to evaluate TC by assessing the combined influence of air temperature, humidity, air velocity, metabolic rate, and clothing insulation. Figure 7.10 provides a comprehensive overview of PMV variations throughout the office.

The results indicate that most areas in Zone 1 exhibit PMV values between -1 and 0, providing moderate TC. Occupants near the open window experience slightly colder conditions, with PMV values reaching -2 due to direct exposure to outdoor air. In contrast, Zones 2 and 3 exhibit PMV values around 1, indicating a slight tendency toward warm conditions, which is attributable to limited airflow regulation and heat accumulation near the ceiling.



(a) z = 1 m

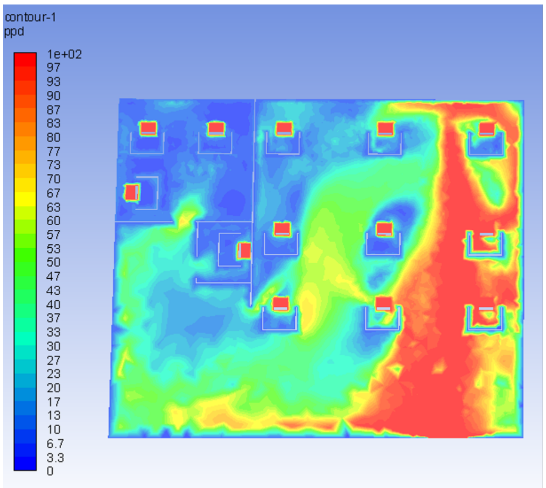


(b) z = 2 m

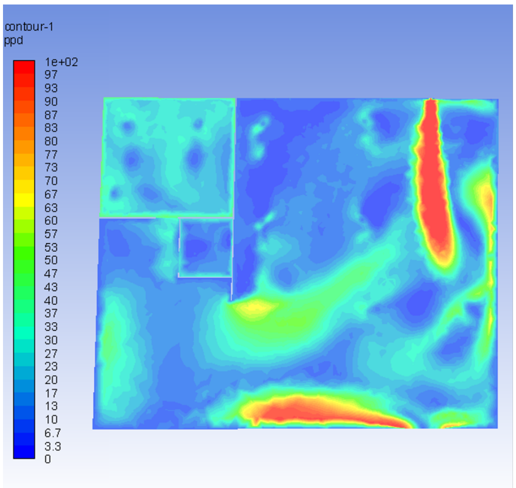
Figure 7.10: PMV contour in z direction during Scenario 2 of mixed ventilation.

The PPD index quantifies occupant discomfort levels based on deviations from optimal TC conditions. Figure 7.11 provides a comprehensive overview of PPD variations throughout the office.

The results indicate that most areas in all three zones exhibit moderate discomfort, with PPD values ranging between 20% and 50%. Higher PPD values are observed near the open window in Zone 1, where direct exposure to cold outdoor air significantly impacts occupant comfort. Thermal discomfort remains widespread, but conditions are significantly improved compared to Scenario 1. AC has a limited impact on mitigating the effects of cold outdoor air intrusion, particularly in areas directly affected by NV airflow.



(a) z = 1 m



(b) z = 2 m

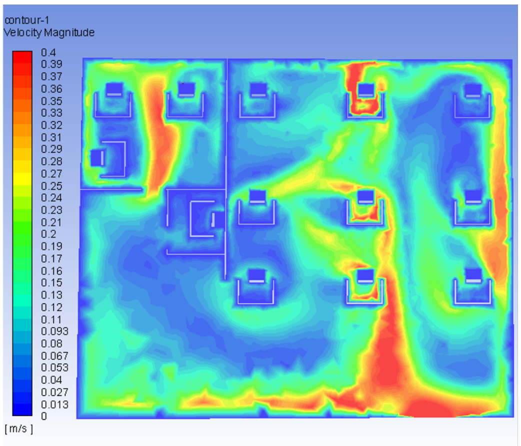
Figure 7.11: PPD contour in z direction during Scenario 2 of mixed ventilation.

7.5.3 Scenario 3

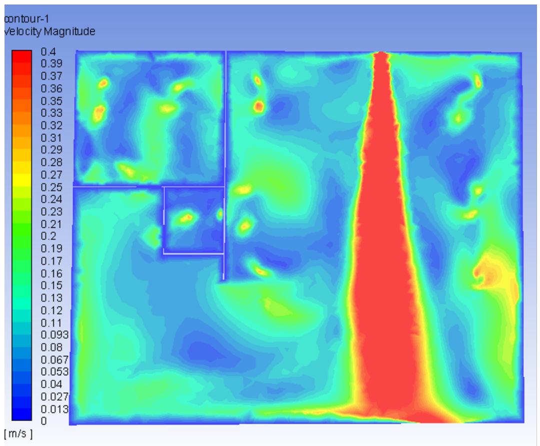
7.5.3.1 Air Velocity Pattern

Scenario 3 represents a summer ventilation condition, which incorporates a different window opening (Window 6) and adjusted AC placement in Zone 2. The velocity contours presented in Figure 7.12 provides a comprehensive overview of the air velocity distribution.

The findings of Scenario 3 suggest that the adjustment of AC placement significantly influences airflow distribution, with Zone 2 benefiting the most from improved ventilation efficiency. In contrast, Zone 3 continues to exhibit limited airflow penetration, indicating the need for additional ventilation strategies to enhance circulation in this enclosed area.



(a) z = 1 m



(b) z = 2 m

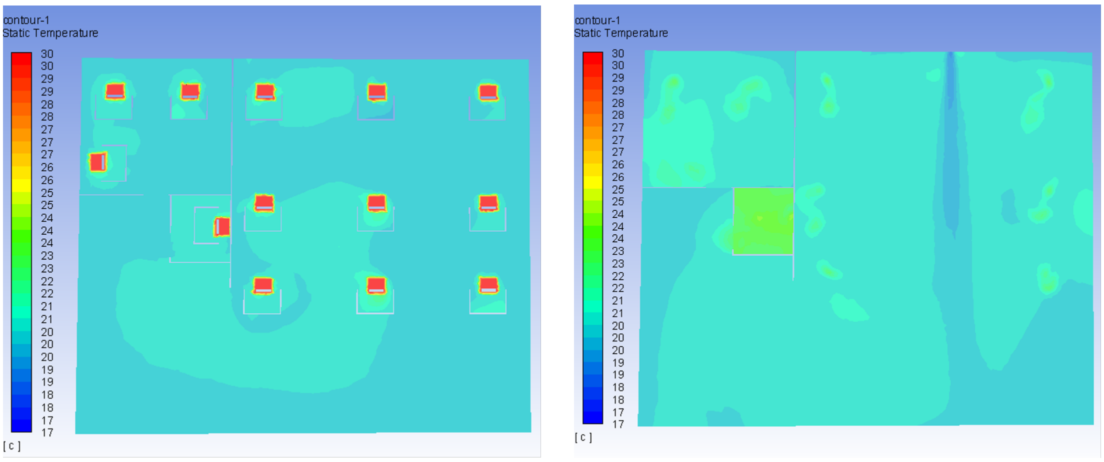
Figure 7.12: Air velocity contour in z direction during Scenario 3 of mixed ventilation.

7.5.3.2 Room Temperature and Relative Humidity

The room temperature distribution in Scenario 3 reflects the combined influence of NV and AC on the maintenance of TC in the home. Figure 7.13 provides an overview of the temperature distribution throughout the office layout.

The results demonstrate that mixed ventilation successfully maintained indoor temperatures within an optimal range, with NV effectively cooling Zone 1 and AC supporting temperature regulation in Zones 2 and 3.

In general, the temperature distribution in Scenario 3 is in good agreement with the TC standards. Indoor temperatures remain within an acceptable range, with most areas between 20 °C and 22 °C, which is within the recommended comfort range according to the Fishman survey [260, 337]. This suggests that the mixed-ventilation strategy employed in this scenario effectively maintains a thermally comfortable environment throughout the office space.



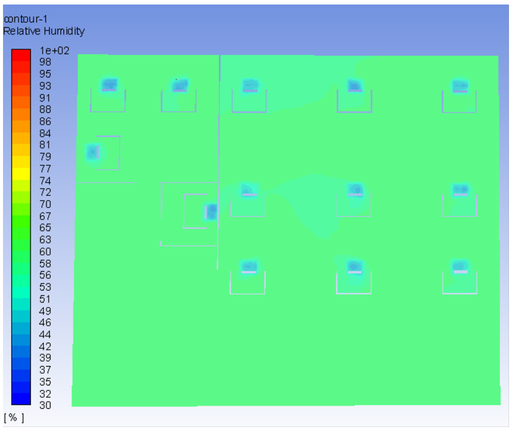
(a) z = 1 m (b) z = 2 m

Figure 7.13: Temperature contour in z direction during Scenario 3 of mixed ventilation.

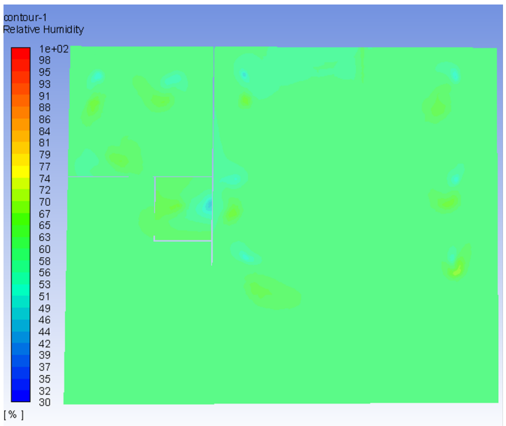
The distribution of RH in Scenario 3 illustrates the combined effects of NV (introduced through an open window) and AC (provided by the AC system).

Figure 7.14 provides a broader perspective of the distribution of RH across the office.

The results indicate that most areas in Zones 1, 2, and 3 experience levels of RH around 60%, with some areas slightly exceeding this threshold. These findings suggest that NV and AC contribute to maintaining a stable and comfortable RH level throughout the office.



(a) z = 1 m



(b) z = 2 m

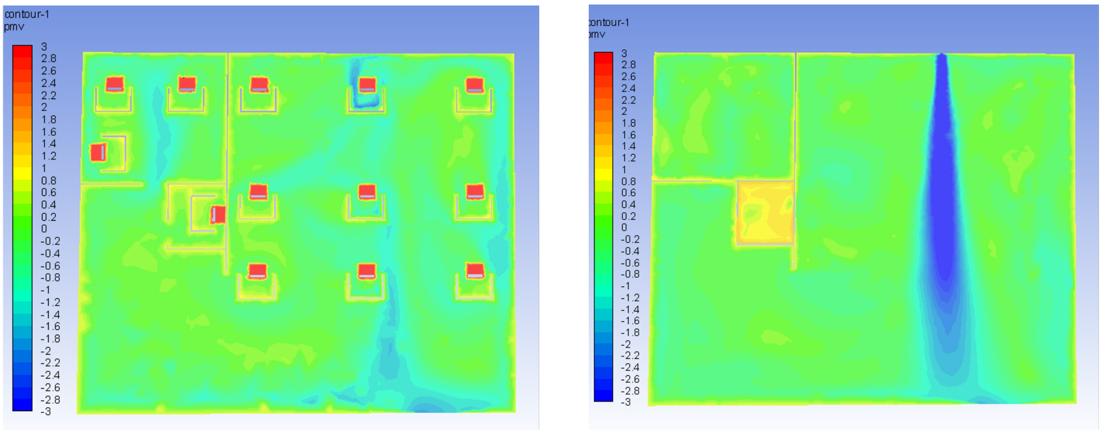
Figure 7.14: RH contour in z direction during Scenario 3 of mixed ventilation

7.5.3.3 Predicted Mean Vote and Predicted Percentage of Dissatisfied

The distribution of PMV values in the three office zones in Scenario 3 demonstrates the influence of NV and AC on indoor thermal sensations, as depicted in Figures 7.15.

The results indicate that most areas in all three zones maintain optimal TC, with PMV values between -0.5 and 0.5. Zone 3 exhibits slightly higher PMV values, reaching up to 1.2, particularly near the ceiling, where the accumulation of heat is more pronounced due to limited air circulation. However, at the occupant level, the PMV remains within the acceptable comfort range.

Scenario 3 demonstrates a well-balanced thermal environment, effectively maintained through the combined use of NV and AC. The AC system in Zone 2 successfully regulates the temperature, while NV in Zone 1 ensures stable airflow and comfort conditions. Although Zone 3 experiences slightly higher PMV values near the ceiling, the overall thermal environment remains within the recommended comfort levels, strengthening the effectiveness of the mixed ventilation approach.



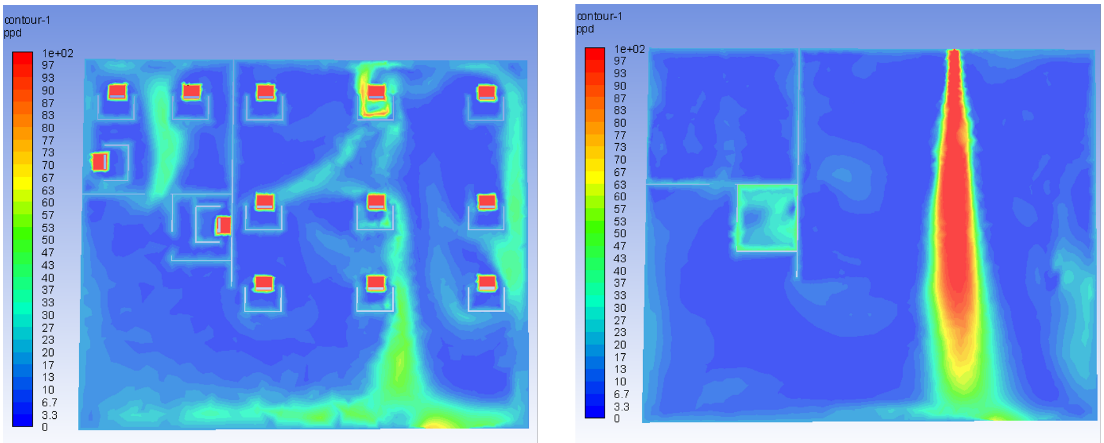
(a) z = 1 m (b) z = 2 m

Figure 7.15: PMV contour in z direction during Scenario 3 of mixed ventilation.

The PPD index quantifies occupant discomfort based on deviations from optimal thermal conditions. In this scenario, with an outdoor temperature of 19 °C, NV through an open window in Zone 1, and AC operating at 13 °C in Zone 2, the PPD distribution is analysed to assess the effectiveness of the mixed-ventilation strategy. Figure 7.16 provides a comprehensive overview of PPD variations throughout the office.

The results indicate that most areas in all three zones exhibit excellent TC, with PPD values of 10% or lower. Localised areas near room corners exhibit slightly higher PPD values, ranging between 10% and 20%. The combination of NV in Zone 1 and AC in Zone 2 effectively regulates indoor conditions, ensuring a balanced airflow and temperature distribution throughout the office.

Scenario 3 demonstrates optimal thermal conditions, with low PPD values in all zones, confirming that the mixed-ventilation strategy (open window in Zone 1 and AC in Zone 2) was highly effective. This configuration successfully maintained indoor comfort, minimised discomfort, and ensured a well-ventilated environment. The PPD values in most areas remain below 10%, further validating the efficiency of this approach in achieving thermal satisfaction for the occupants.



(a) z = 1 m (b) z = 2 m

Figure 7.16: PPD contour in z direction during Scenario 3 of mixed ventilation.

7.5.3.4 Aerosol Dispersion and Infection risk

Coughing is a primary mechanism for the airborne virus transmission of infectious aerosols in enclosed environments. The current analysis examines the dispersion dynamics of expelled particles under mixed ventilation conditions specifically in Scenario 3, where both NV (through an open window in Zone 1) and AC (AC in Zone 2) influence airflow patterns. A coughing velocity of 11.8 m/s was applied and the aerosol dispersion was analysed for four different infected individuals positioned in different locations of the office, further away from both the open window and the AC unit. The following results illustrate the spatial and temporal movement of particles in the X, Y, and Z directions, highlighting how airflow affects their dispersion.

Figure 7.17 presents the spatial distribution of aerosols expelled by the first infected individual during coughing. Initially, the expelled particles exhibit highly concentrated forward movement, but they undergo significant dispersion as they interact with indoor airflow. A dense accumulation of aerosols is observed near the source, but due to ventilation effects the particles disperse throughout the office space, potentially exposing multiple occupants.

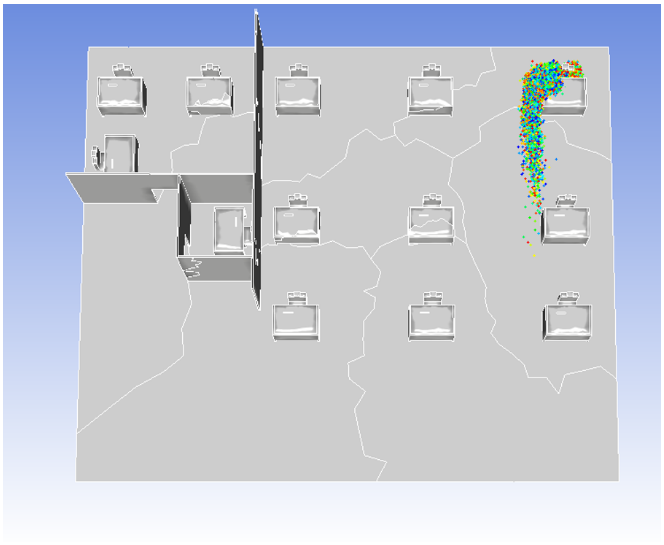


Figure 7.17: Particle transmission from the first infected individual during coughing.

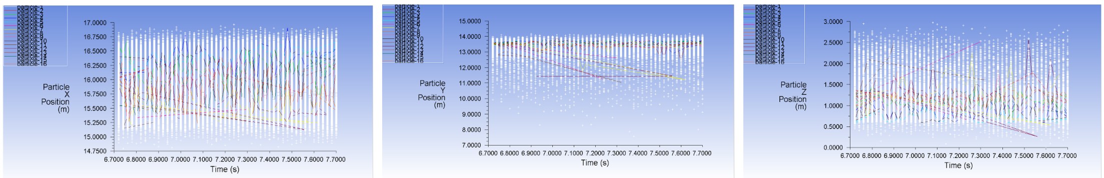
Figure 7.18 illustrates the aerosol dispersion along the X, Y, and Z directions during the coughing event for the first individual.

Figure 7.18-(a) illustrates the movement of aerosols along the X axis. The results show an initial rapid displacement due to the high velocity of coughing, which propels the particles forward. Most particles remain within the 15.25 m to 16.75 m range (indicating a transmission distance of approximately 1.5 m), indicating limited lateral spread under current airflow conditions. However, recirculation effects from AC contribute to the movement of the particles within a confined region.

Figure 7.18-(b) highlights the lateral diffusion along the Y axis, with particle displacement values ranging between 11.75 m and 13.75 m (indicating a transmission distance of approximately 2 m). This suggests that horizontal airflow patterns significantly impact the way aerosols spread throughout the office. The interaction between NV and AC improves lateral dispersion, potentially increasing the

risk of exposure of nearby occupants.

Figure 7.18-(c) represents the vertical particle distribution along the Z axis, where most aerosols remain between 0.5 m and 2.5 m (indicating a transmission distance of approximately 2 m). This aligns with the breathing zone of seated and standing occupants, increasing the likelihood of inhalation by individuals within this zone. The data indicate minimal upward or downward dispersion beyond 2.5 m, highlighting that airborne virus transmission risk remains highest at the occupant level.



(a) X direction (b) Y direction (c) Z direction

Figure 7.18: Aerosol dispersion through coughing on X, Y, and Z directions for the first individual during mixed ventilation.

Figure 7.19 shows the spatial dispersion of aerosols expelled by the second infected individual during coughing. Initially, the particles display a concentrated forward trajectory before dispersing as they interact with the air flow of the room. Unlike the first infected individual, who was positioned near the ventilation sources, the expelled particles of the second infected individual appear more localised, with less pronounced dispersion throughout the office. However, aerosols are still widely distributed in the immediate vicinity, posing a potential airborne virus transmission risk to nearby occupants.

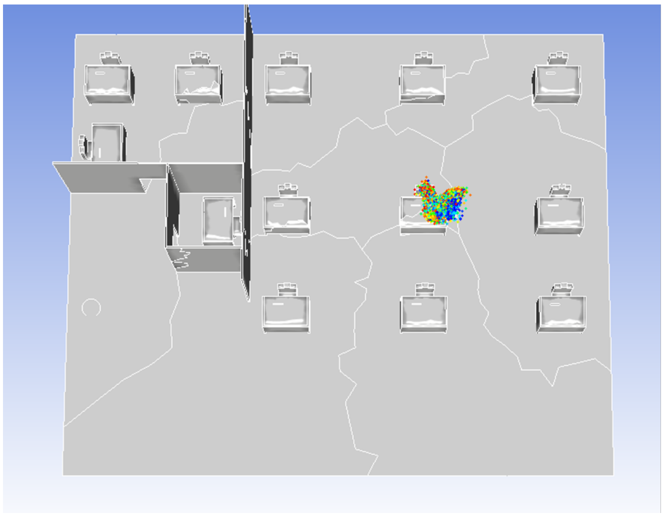


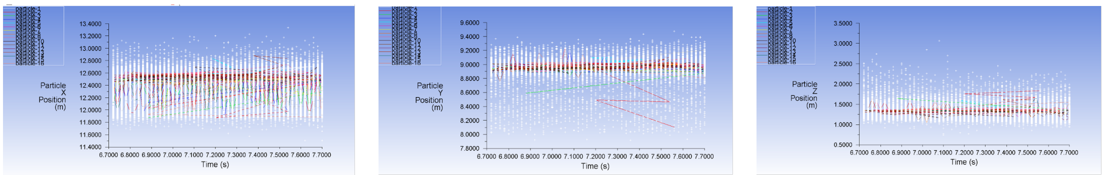
Figure 7.19: Particle transmission from the second infected individual during coughing.

Figure 7.20 illustrates the aerosol dispersion along the X, Y, and Z directions during the coughing event for the second individual.

Figure 7.20-(a) shows that the movement of the particles along the X axis exhibits a stable dispersion pattern, mainly concentrated between 11.9 m and 12.8 m (indicating a transmission distance of approximately 0.9 m). Compared to the first infected individual, the lateral spread is more contained, suggesting that the airflow influence is less turbulent in this part of the room. The reduced dispersion in this direction could be attributed to the distance from both the AC and the window, limiting the strong airflow-induced movement.

The dispersion in the Y direction, as presented in Figure 7.20-(b), highlights that the lateral diffusion of particles along the Y axis is more constrained, remaining within a range of 8.6 m to 9.2 m (indicating a transmission distance of approximately 0.8 m). The data indicate that airflow interactions in this zone cause moderate horizontal movement, but particles remain largely near their initial source. The absence of direct airflow currents from the AC or window results in a more central accumulation of aerosols around the infected individual.

The dispersion in the Z direction, illustrated in Figure 7.20-(c), shows that the vertical distribution of the aerosols remains within 1 to 1.75 m (indicating a transmission distance of approximately 0.75 m), corresponding to the breathing height of most of the occupants. Similarly to the first infected individual, the dispersion remains concentrated within the respiratory zone, strengthening the high transmission risk for individuals seated nearby. However, compared to the first infected individual, the lower vertical displacement suggests weaker upward airflow currents, likely due to the lack of strong forced ventilation effects in this section of the office.



(a) X direction (b) Y direction (c) Z direction

Figure 7.20: Aerosol dispersion through coughing in X, Y, and Z directions for the second individual during mixed ventilation.

Figure 7.21 demonstrates the spatial distribution of aerosols expelled by the third infected individual. The expelled particles initially exhibit a concentrated forward movement before undergoing dispersion influenced by indoor airflow. Due to the position of this individual, particle dispersion remains relatively localised, with minimal spread towards distant occupants.

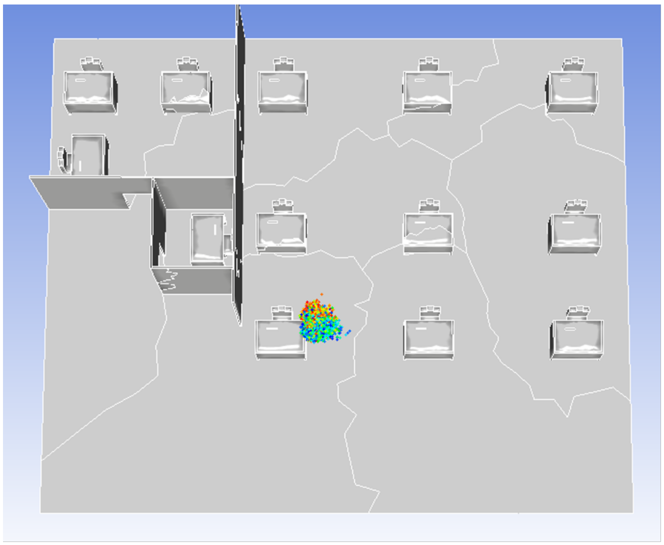


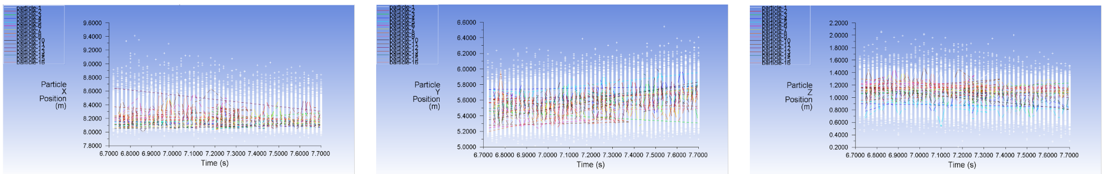
Figure 7.21: Particle transmission from the third infected individual during coughing.

Figure 7.22 illustrates the aerosol dispersion along the X, Y, and Z directions during the coughing event for the third individual.

Figure 7.22-(a) displays the movement of the particles in the X direction over time. The particles exhibit a slow and limited displacement compared to other cases, primarily restricted between 8 m and 8.6 m (indicating a transmission distance of approximately 0.6 m). This indicates a weaker lateral movement due to reduced airflow influence in this corner of the office.

In the Y direction (Figure 7.22-(b)), the lateral dispersion remains within a short range of 5.2 m to 5.9 m (indicating a transmission distance of approximately 0.7 m). This suggests that the expelled aerosols remain highly concentrated near the source, with minimal spread across the office.

In the Z direction (Figure 7.22-(c)), the particles remain within a height range of 0.7 m to 1.4 m (indicating a transmission distance of approximately 0.7 m), which aligns with the standard breathing zone of seated and standing individuals. The limited vertical dispersion further indicates that the airflow circulation in this area is weak, leading to the accumulation of aerosols near the source.



(a) X direction (b) Y direction (c) Z direction

Figure 7.22: Aerosol dispersion through coughing in X, Y, and Z directions for the third individual during mixed ventilation.

Figure 7.23 illustrates the aerosol dispersion pattern for the fourth infected individual, positioned in Zone 2, where the AC system is operational. The AC system plays a dominant role in controlling the dispersion of expelled particles, leading to a more confined spread compared to individuals located in Zone 1. The results indicate that the presence of the AC unit helps limit long-range dispersion, effectively reducing the risk of spread of infection to distant areas.

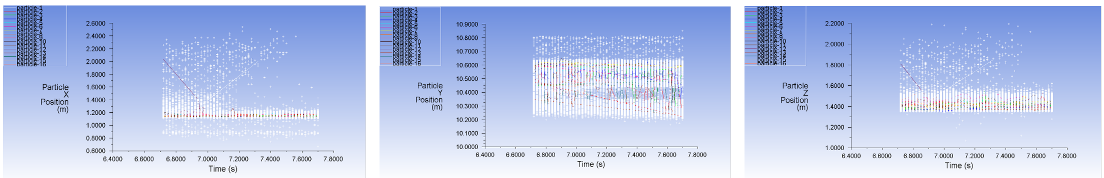
Figure 7.23: Particle transmission from the fourth infected individual during coughing.

Figure 7.24 illustrates the aerosol dispersion along the X, Y, and Z directions during the coughing event for the fourth individual.

Figure 7.24-(a) shows the displacement of the particles in the X direction over time. particles initially move forward due to the coughing velocity, but remain concentrated within a small range from 1.1 m to 2 m after 6.7 seconds (indicating a transmission distance of approximately 0.9 m). The limited movement suggests that the airflow pattern in Zone 2, influenced by the AC unit, effectively restricts the particles from spreading throughout the office.

The dispersion in the Y direction, as shown in Figure 7.24-(b), highlights the lateral movement of the particles, with the dispersion constrained between 10.2 m and 10.6 m after 6.7 seconds (indicating a transmission distance of approximately 0.4 m). Unlike the individuals in Zone 1, where NV led to significant lateral spread, the AC unit in this zone appears to regulate airflow, preventing excessive horizontal movement.

In the vertical (Z) direction, Figure 7.24-(c) shows the vertical distribution of aerosols, which remains within 1.3 m to 1.8 m after 6.7 seconds (indicating a transmission distance of approximately 0.5 m). This range corresponds to the breathing zone of most occupants, indicating that while the AC system helps contain dispersion, expelled particles still accumulate at levels where transmission risk remains present.



(a) X direction (b) Y direction (c) Z direction

Figure 7.24: Aerosol dispersion through coughing in X, Y, and Z directions for the fourth individual during mixed ventilation.

Sneezing is a powerful mechanism for the expulsion of infectious aerosols at high velocity, significantly increasing the risk of rapid airborne virus transmission. Compared to coughing, sneezing generates a more powerful expulsion of particles, resulting in a faster and wider dispersion within an indoor environment. In this analysis, a sneezing velocity of 70 m/s was applied in Scenario 3, where mixed ventilation (consisting of NV through an open window in Zone 1 and AC through an AC unit in Zone 2) played a key role in influencing airflow dynamics and particle dispersion. This study focused on four infected individuals, analysing the spatial and temporal dispersion of particles along the X, Y, and Z directions to evaluate the impact of ventilation strategies on aerosol transmission.

Figure 7.25 illustrates the spatial distribution of aerosols expelled by the first infected individual during sneezing. Compared to coughing, sneezing results in a higher concentration of particles that disperse more widely due to the increased initial velocity. The particles exhibit a strong forward trajectory before interacting with the surrounding airflow, leading to a notable dispersion pattern.

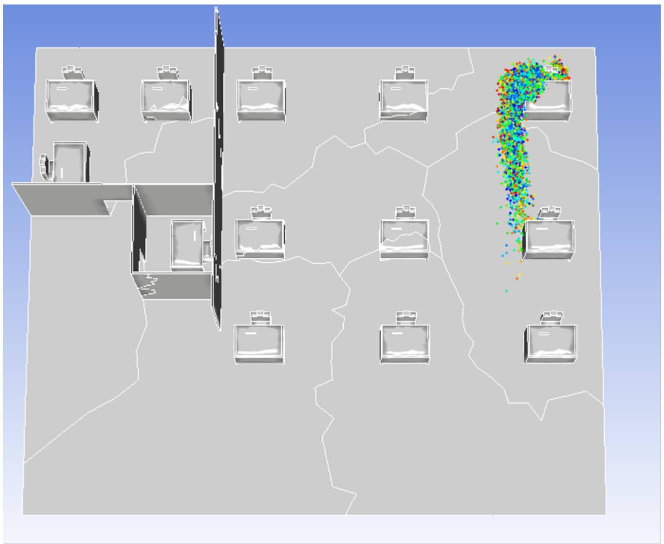


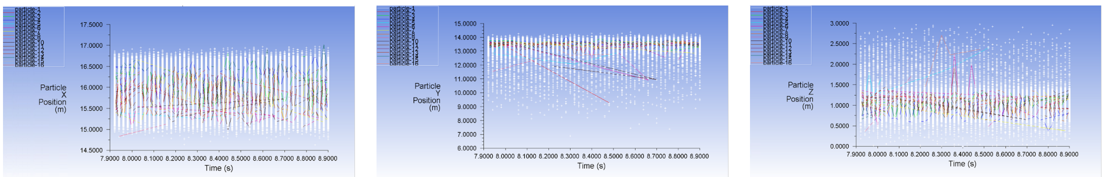
Figure 7.25: Particle transmission from the first infected individual during sneezing.

Figure 7.26 illustrates the aerosol dispersion along the X, Y, and Z directions during the sneezing event for the first individual.

As shown in Figure 7.26-(a), the particles initially experience a rapid displacement along the X axis, reaching distances between 15 m and 16.75 m within the observed time frame (indicating a transmission distance of approximately 1.75 m). Unlike coughing, where the particles tended to remain more localised, sneezing results in a more extensive spread, suggesting that the high initial velocity enables the particles to travel further before settling.

Figure 7.26-(b) presents the lateral spread of particles along the Y axis. The results indicate that the particles disperse within a range of 9.5 m to 14 m (indicating a transmission distance of approximately 4.5 m), highlighting a significant horizontal spread due to airflow interactions. This is particularly important because it shows the potential for cross-contamination among multiple occupants located along the lateral airflow pathways.

Figure 7.26-(c) illustrates the vertical distribution of aerosolised particles along the Z axis. The results show that the particles remain largely between 0.5 m and 2.5 m (indicating a transmission distance of approximately 2 m), indicating a strong presence within the typical breathing zone of nearby occupants. Unlike coughing, where the spread was more contained, sneezing results in a more unpredictable vertical spread, increasing the potential for airborne transmission.



(a) X direction (b) Y direction (c) Z direction

Figure 7.26: Aerosol dispersion in X, Y, and Z directions for the first individual during mixed ventilation.

Figure 7.27 presents the spatial distribution of aerosols expelled from the second infected individual. The particles initially travel in a concentrated forward motion before dispersing as a result of the interaction with indoor airflow. Unlike the first infected individual, where the particles spread rapidly toward the door due to strong NV, the dispersion of the second infected individual is more contained within the zone due to its location farther from the window and AC unit.

Figure 7.27: Particle transmission from the second infected individual during sneezing.

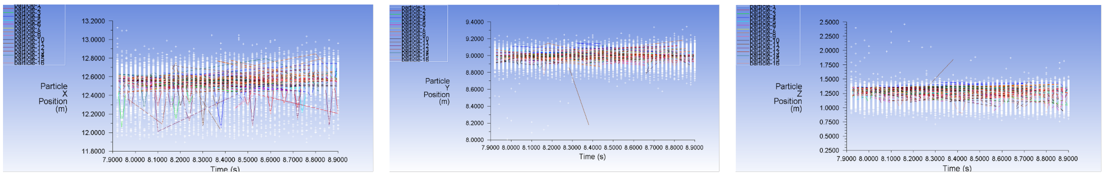
Figure 7.28 illustrates the aerosol dispersion along the X, Y, and Z directions during the sneezing event for the second individual.

As illustrated in Figure 7.28-(a), the particles exhibit an initial rapid displacement in the X direction due to the high forward velocity of the sneeze. However, their movement remains restricted within the range of approximately 12.0 m to 12.8 m after 7.9 seconds (indicating a transmission distance of approximately 0.8 m). This is likely due to the central positioning of the second infected individual, where neither the window nor the AC unit fully directs the airflow, reducing the lateral spread.

Figure 7.28-(b) depicts the lateral movement of the particles in the Y direction. The dispersion is relatively limited, with particle displacement values ranging between 8.8 m and 9.2 m after 7.9 seconds (indicating a transmission distance of approximately 0.4 m). This is likely due to the central positioning of the second

infected individual, where neither the window nor the AC unit fully directs the airflow, reducing the lateral spread.

The vertical distribution of the expelled aerosols, shown in Figure 7.28-(c), indicates that the particles remain predominantly within 1 m to 1.5 m after 7.9 seconds (indicating a transmission distance of approximately 0.5 m). This range corresponds to the breathing zone of most occupants, highlighting a high airborne virus transmission risk in this area. Unlike the first infected individual, whose particles increased more due to strong vertical airflow near the window, the spread for the second infected individual is more restricted in the vertical direction.



(a) X direction (b) Y direction (c) Z direction

Figure 7.28: Aerosol dispersion in X, Y, and Z directions for the second individual during mixed ventilation.

Figure 7.29 illustrates the overall spatial distribution of aerosols expelled by the third infected individual. The results indicate that the particles remained relatively concentrated around the source because of the location of the individual, which was far from the direct airflow pathways generated by the open window and the AC. Most of the particles dispersed locally, with some lateral spread occurring due to weak indoor air currents.

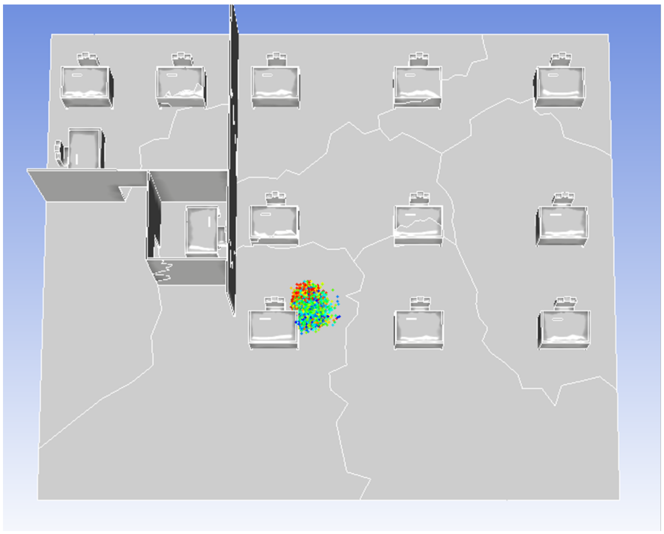


Figure 7.29: Particle transmission from the third infected individual during sneezing..

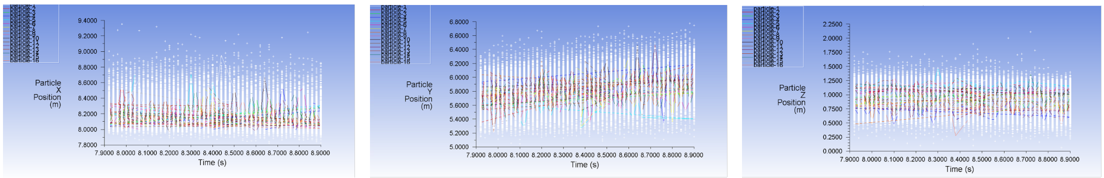
Figure 7.30 illustrates the aerosol dispersion along the X, Y, and Z directions during the sneezing event for the third individual.

Figure 7.30-(a) shows the movement of the particles in the X direction over time. The aerosols initially exhibit strong forward motion due to the high velocity of the sneeze. However, after approximately 7.9 seconds, the dispersion becomes limited, with particles remaining within a range of 8 m to 8.6 m (indicating a transmission distance of approximately 0.6 m). This indicates that in the absence of strong directional airflow, the particles settle within a confined region.

The lateral dispersion of the particles in the Y direction is depicted in Figure 7.30-(b). The results show that aerosols remain within 5.3 m to 6.2 m (indicating a transmission distance of approximately 0.9 m), indicating a moderate spread. Unlike infections closer to airflow sources, the particles here exhibit a more localised dispersion pattern, suggesting minimal influence from cross-zone air currents.

Figure 7.30-(c) represents the vertical dispersion of particles. The results indicate that most aerosols remain within 0.5 m to 1.25 m (indicating a transmission

distance of approximately 0.75 m), primarily within the breathing zone of the occupants. The containment of particles within this critical zone highlights the potential risk of airborne virus transmission in the immediate vicinity of the infected individual.



(a) X direction (b) Y direction (c) Z direction

Figure 7.30: Aerosol dispersion in X, Y, and Z directions for the third individual during mixed ventilation.

Figure 7.31 illustrates the spatial distribution of particles expelled from the fourth individual's position. The results show that sneezing leads to a localised dispersion of aerosols with minimal spread beyond the immediate surroundings. Unlike scenarios where NV (open window) dominates, the airflow regulation of the AC system in Zone 2 appears to limit the extent of aerosol movement, which contains the majority of particles near the infected individual.

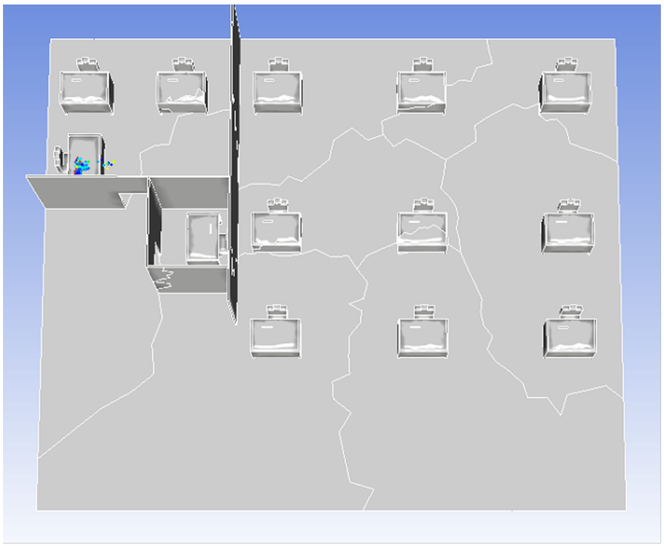


Figure 7.31: Particle transmission from the fourth infected individual during sneezing.

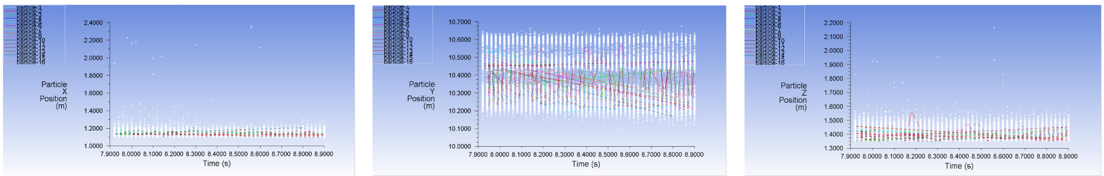
Figure 7.32 illustrates the aerosol dispersion along the X, Y, and Z directions during the sneezing event for the fourth individual.

As depicted in Figure 7.32-(a), the displacement in the X direction remains highly constrained. After 7.9 seconds, expelled particles remain within a short range of 1.1 m to 1.2 m (indicating a transmission distance of approximately 0.1 m), suggesting low forward momentum due to airflow stabilisation by the AC system. Compared to infections in Zone 1, where NV significantly increased aerosol reach, controlled airflow in Zone 2 reduces forward travel.

Figure 7.32-(b) shows the movement in the Y direction, where the particles initially exhibit a slight lateral spread but remain between 10.2 m and 10.6 m (indicating a transmission distance of approximately 0.4 m). This suggests that while there is some lateral dispersion, it is significantly less pronounced than in NV areas, where the particles spread widely. The AC system appears to regulate the horizontal flow, preventing excessive spread.

Figure 7.32-(c) demonstrates the vertical movement (Z) of the expelled particles.

The aerosols remain between 1.35 m and 1.5 m after 7.9 seconds (indicating a transmission distance of approximately 0.15 m), aligning closely with the typical breathing zone of the occupants. This implies that although the AC system effectively limits the overall dispersion, residual aerosols still accumulate at a height where the risk of inhalation remains high.



(a) X direction (b) Y direction (c) Z direction

Figure 7.32: Aerosol dispersion in X, Y, and Z directions for the fourth individual during mixed ventilation.

7.6 Discussion

This section provides a comprehensive discussion of the results obtained from the three mixing ventilation scenarios, focussing on airflow patterns, IAQ, room temperature, RH, TC indices (PMV and PPD), and aerosol dispersion. The findings are compared with the ASHRAE, EN 16798, and ISO 7730 standards for acceptable indoor conditions to identify optimal and suboptimal configurations and suggest recommendations for improved ventilation performance.

7.6.1 Comparison with ASHRAE, EN 16798, and ISO 7730 Standards

The mixed-mode ventilation scenarios were evaluated against the TC criteria outlined in ASHRAE 55, ISO 7730, and EN 16798. These standards define acceptable

PMV and PPD to ensure a comfortable indoor environment. ASHRAE 55 specifies an occupancy satisfaction level of 80%, corresponding to a PMV range of -0.5 to +0.5 and a PPD below 20%, while ISO 7730 and EN 16798 classify comfort into three categories:

- Category A (ISO)/I (EN): PMV within ±0.2 and PPD < 6% (high expectations)
- Category B (ISO)/II (EN): PMV within ±0.5 and PPD < 10% (normal expectations)
- Category C (ISO)/III (EN): PMV within ±0.7 and PPD < 15% (moderate comfort)

TC performance varied between different mixed mode configurations, some scenarios successfully maintaining recommended conditions, while others presented deviations due to poor air distribution and excessive RH.

Scenario 1 exhibited significant deviations from the ASHRAE TC criteria. PMV values ranged from -2 to -3, indicating extreme cold discomfort. This resulted in PPD values exceeding 50%, meaning that more than half of the occupants experienced thermal discomfort, which is far outside the ASHRAE and ISO recommended limits.

The room temperature dropped below 18 °C, which does not meet the recommended comfort range of ASHRAE 55 of 22 °C to 26 °C. Furthermore, RH levels exceeded 80%, exceeding the ASHRAE guideline of 30% to 0%. High levels of RH increase the risks of microbial growth and improve the stability of airborne viruses, further degrading IAQ.

The air velocity was highly uneven, with some areas experiencing excessive cold draughts due to open windows, while other sections had stagnant air pockets. The recommended indoor airflow velocity of ASHRAE is 0.1 m/s to 0.25 m/s, but in Scenario 1, the cold outdoor air created high local speeds, exacerbating discomfort in exposed areas.

Scenario 2 demonstrated a significant improvement over Scenario 1, with PMV values ranging from -1 to 0.6 in Zone 1 and 0 to 1.6 in Zones 2 and 3. This suggests that TC was maintained largely at the occupant level, keeping PPD values below 10%, aligned with ASHRAE 55, ISO Category B, and EN Category II.

However, at higher elevations, the PMV values increased to 1.6 and the PPD exceeded 20%, indicating thermal stratification. This suggests that warm air accumulated at higher levels due to insufficient air mixing, leading to comfort inconsistencies between vertical zones.

RH exceeded 65%, exceeding the optimal ASHRAE range of 30% to 60%. Elevated RH can increase the stability of airborne viruses and create conditions conducive to mould growth, leading to degradation of IAQ. This issue suggests a need for enhanced dehumidification controls to maintain compliance with ASHRAE recommendations.

Scenario 3 exhibited the most stable and balanced conditions, maintaining PMV values within the recommended range of ASHRAE (-0.5 to +0.5) in all zones. This indicates that the thermal conditions remained relatively stable, ensuring compliance with the comfort levels of ISO Category B / EN Category II.

The temperature was maintained between 20 °C and 22 °C, fully in accordance with the recommendations of ASHRAE 55. Furthermore, RH was kept within the optimal 40% to 60% range, ensuring a better IAQ compared to Scenario 1 and Scenario 2.

The air velocity was well controlled and most areas were within the recommended range of 0.1 m/s to 0.25 m/s of ASHRAE. Unlike the previous scenarios, Scenario 3 had fewer stagnant zones and better airflow uniformity, reducing the risk of uneven thermal conditions or localised air stagnation.

7.6.2 Identification of Dead Zones in Mixed-mode Ventilation

Dead zones, defined as regions with minimal airflow ($<$ 0.1 m/s), present a critical challenge in indoor air distribution, leading to poor air mixing, localised temperature imbalances and stagnant pollutant accumulation. According to ASHRAE Standard 62.1, adequate air circulation is essential to prevent air stagnation because stagnant zones can compromise TC and increase the occupant's exposure to airborne contaminants.

Across the three mixed-mode ventilation scenarios, dead zones were consistently identified in Zones 2 and 3, particularly in areas shielded from primary airflow pathways, such as room corners, spaces far from ventilation inlets, and regions obstructed by furniture. These stagnant regions exhibited temperature stratification, elevated levels of HR ($>$ 70%), and reduced dilution efficiency of indoor pollutants.

Scenario 1 (winter conditions, outdoor temperature 4 °C) exhibited significant dead zones, particularly in Zones 2 and 3, where the air velocity remained below 0.1 m/s. The lack of a sufficient airflow distribution of the AC exacerbated stagnation, leading to poor heat distribution, extreme cold stress (PMV = -2 to -3), and high dissatisfaction (PPD $>$ 50%).

Furthermore, some areas in Zone 1 near the open window experienced an excessive air velocity (0.4 m/s) due to the direct influx of cold outside air. This resulted in localised discomfort, highlighting an imbalance in airflow, where certain areas received excessive ventilation, while others remained stagnant. These findings underscore the need for a more controlled integration of NV and AC to prevent extreme airflow discrepancies within occupied spaces.

Scenario 2 (winter conditions, outdoor temperature 13°C) showed notable improvements in airflow distribution, with an air velocity that reaches 0.08 m/s to 0.2 m/s in most areas. However, dead zones persisted in Zone 3 and room corners in Zone 1, where airflow remained below 0.1 m/s, indicating areas of inadequate ventilation.

A key factor contributing to the improved ventilation performance in Scenario 2 was the strategic placement of Window 4 in the middle section of Zone 1, which facilitated a more uniform airflow pattern. Unlike Scenario 1, where high-velocity airflow caused direct occupant discomfort, this centralised window placement helped distribute air more evenly, reducing thermal asymmetry.

Despite these improvements, Zone 3 remained stagnant due to its distance from both the AC unit (located in Zone 2) and the NV source (open window in Zone 1). This finding suggests that NV alone was not sufficient to induce adequate circulation in all zones, emphasising the need for AC reinforcements to improve air mixing.

Scenario 3 (summer conditions, outdoor temperature 19°C) exhibited the most balanced airflow distribution, with air velocity reaching 0.2 m/s in most areas and minimal dead zones. The combination of NV and AC, achieved through an open window in Zone 1 (Window 6) and AC operation in Zone 2, effectively improved air circulation and pollutant dispersion.

Although minor dead zones persisted in Zone 3, where air velocity occasionally dropped below 0.1 m/s, this issue was less pronounced compared to previous scenarios. Furthermore, elevated airflow velocities (0.4 m/s) were recorded in seating areas near the open window, confirming that window positioning played a critical role in regulating airflow and TC.

Scenario 3 also demonstrated the most effective airflow management strategy, characterised by the following:

- Reduced air stagnation, ensuring consistent air mixing across all zones.
- Optimised temperature regulation within 20 °C to 23 °C, which aligns well with the recommendations of ASHRAE 55.
- RH levels maintained within the recommended range of ASHRAE (30% top 60%), reducing the risk of stability of airborne viruses and mould growth.

7.6.3 Impact of Air Velocity on Virus Dispersion

Air velocity plays a critical role in determining the dispersion, transport, and retention time of airborne contaminants, particularly in enclosed office environments. In this study, CFD simulations analysed aerosol dispersion during coughing and sneezing events under Scenario 3 (mixed-mode ventilation), where both NV (Window 4) and AC (an AC unit in Zone 1) were active. The results demonstrated that mixed ventilation significantly altered the trajectory, containment, and dilution efficiency of expelled aerosol particles compared to NV or AC alone. This led to a more controlled dispersion pattern and improved ventilation performance, reducing overall transmission risk.

During simulated coughing and sneezing events, the particles were expelled at 11.8 m/s and 70 m/s, respectively, introducing a significant aerosol load into the indoor air. The airflow distribution was a key determinant of whether these particles remained suspended, were transported across zones, or settled more quickly. Near Window 4 in Zone 1, the first infected individual experienced extensive particle dispersion due to high air velocity exceeding 0.2 m/s. Strong natural air flow facilitated rapid aerosol transport across multiple occupants seated in front of the infected individual, increasing the potential for cross-zone transmission. However, unlike the NV scenario, the AC introduced a controlled air movement that aided in particle dilution, limiting prolonged airborne retention. Although NV alone led to a more unpredictable and widespread dispersion of particles, the combination of

AC-driven airflow and window-induced ventilation helped contain the movement of expelled aerosols more effectively in mixed ventilation.

In contrast, the second and third infected individuals, who are positioned centrally and in the left-hand corner of Zone 1, experienced more localised particle dispersion due to lower air velocities (0.2 m/s or less). The reduced not only airflow minimised the excessive horizontal spread but also prolonged the suspension of aerosols, increasing the risk of localised exposure. Compared to NV alone, where airflow patterns were inconsistent and aerosol dispersion was more widespread, mixed ventilation created a more structured and stable airflow, limiting erratic movement and containing particles more effectively.

In Zone 2, where Infected 4 was located, the absence of direct AC airflow led to lower air velocities (0.2 m/s or less), restricting the dispersion of the lateral aerosol. Although airflow from Zone 1 influenced some movement, particle dilution was considerably slower in this area, resulting in a longer retention time for airborne particles. Unlike Zone 1, where AC and window-driven airflow facilitated more dynamic movement and dilution, Zone 2's reduced air velocity contributed to prolonged aerosol suspension, potentially increasing the risk of exposure of the occupant.

Compared to NV alone, where airflow was often uncontrolled and highly dependent on outdoor wind conditions, mixed ventilation provided more structured airflow regulation, reducing unpredictable aerosol dispersion. It also improved faster aerosol dilution rates, particularly in Zone 1, where the combined effect of AC and natural airflow significantly improved particle clearance. Furthermore, mixed ventilation prevented excessive high-velocity dispersion near openings, which, in NV scenarios, increased transmission risks due to high-speed airflow spreading aerosols across multiple zones.

Compared to AC alone, mixed ventilation improved air exchange between zones, prevented recirculation of indoor air, and improved pollutant removal efficiency.

The introduction of fresh outdoor air helped reduce the risk of accumulation of contaminants, which is often a limitation in fully AC systems. The results also indicated that better air movement uniformity in mixed ventilation helped eliminate stagnant air zones, further decreasing the likelihood of longer airborne virus suspension.

The findings of this study confirm that mixed ventilation provides the most balanced approach to controlling airborne contaminants because it reduces excessive dispersion while improving the efficiency of dilution. Unlike NV alone, which may introduce unpredictable airflow patterns, mixed ventilation helps control aerosol dispersion more effectively. In addition, it mitigates the limitations of AC, which often recirculates indoor air without introducing fresh air, thus increasing the risk of contaminant accumulation. By integrating strategic window placement, AC airflow regulation, and air filtration systems, mixed-mode ventilation can serve as an effective strategy for infection control in office environments.

7.6.4 Impact of Relative Humidity on Comfort and Airborne Virus Stability

RH is a critical factor that influences both TC of the occupant and the stability of airborne viruses, making it a key consideration in indoor environmental control. ASHRAE guidelines recommend maintaining RH between 40% and 60% to optimise comfort and minimise the persistence of airborne pathogens. The findings of the mixed-mode ventilation scenarios demonstrate notable variations in RH levels in different zones, with improved moisture regulation compared to NV alone but some persistent humidity imbalances in certain areas.

Scenario 1 exhibited elevated RH levels, particularly in zones with restricted airflow mixing. RH values at the occupant level ranged from 60% to 65% in Zones 1 and 2, while Zone 3 experienced levels exceeding 70%. The moisture accumulation in Zone 3 can be attributed to low air velocity (<0.1 m/s), which hindered effective moisture dissipation. Furthermore, the RH above the level of the occupant exceeded 65%, indicating a potential moisture stratification in the upper sections of the office, which was exacerbated by the absence of strong AC in this zone.

Excessively high RH levels not only compromise TC but also create an environment that encourages the persistence of airborne viruses [338]. Research suggests that low air velocity contributes to prolonged aerosol suspension, particularly in humid conditions, thereby increasing the risk of airborne virus transmission [339]. These findings indicate that while mixed-mode ventilation introduced some airflow improvements, localised moisture stagnation remained a challenge in areas with inadequate air exchange.

With an increase in outdoor temperature (13 °C), Scenario 2 demonstrated better regulation of RH compared to Scenario 1. RH levels at the occupant level in Zones 1 and 2 ranged from 53% to 60%, gradually decreasing toward the ceiling. This improvement suggests that convective mixing, driven by the AC system, helped redistribute moisture more effectively, reducing excessive accumulation.

However, Zone 3 still exhibited RH levels between 60% and 70%, indicating weaker airflow exchange and limited ventilation-induced dehumidification. Unlike Scenario 1, where humidity accumulation was more widespread, Scenario 2 exhibited more balanced RH control due to increased thermal stratification effects, which helped disperse moisture more evenly across the space.

Scenario 3, representing summer conditions with an open window (Window 6) in Zone 1 and an AC unit operating at 19 °C in Zone 2, exhibited the most stable and well-balanced levels of RH in all zones. RH values at the occupant level ranged from 53% to 60%, remaining within the optimal ASHRAE comfort range. At levels above the occupant, HR remained consistently stable around 60%, demonstrating effective humidity regulation throughout the office space.

The success of Scenario 3 in maintaining RH levels can be attributed to the synergy between NV and AC. The open window in Zone 1 facilitated fresh air exchange, preventing excessive moisture buildup, while the AC unit in Zone 2 introduced conditioned air, reducing latent heat and promoting uniform moisture distribution. Furthermore, Zone 3, which previously exhibited excessive RH in Scenarios 1 and 2, benefited from improved ventilation dynamics, ensuring better moisture dilution and limiting localised humidity accumulation.

In summary, the findings highlight that while mixed-mode ventilation significantly improves RH control compared to NV alone, achieving a uniform humidity balance remains a challenge.

7.6.5 Scenario Performance Evaluation

The performance of the mixed ventilation system was analysed based on air velocity, temperature, RH, TC indices (PMV and PPD), and overall ventilation effectiveness. These key parameters were evaluated to determine how well the integration of AC and NV maintained IAQ and TC under different environmental conditions.

Scenario 1, conducted under winter conditions (outdoor temperature = 4°C), exhibited the worst overall performance among the three cases. The air velocity remained extremely low (< 0.1 m/s) in most zones, leading to stagnant airflow and the formation of dead zones, particularly in Zones 2 and 3. In Zone 1, where an open window and an AC unit were present, air movement was slightly better but high air velocities near the open window (> 0.4 m/s) caused discomfort for occupants seated close to the airflow source.

The temperature distribution highlighted excessive cooling because the open window introduced unregulated cold air (4 °C), drastically lowering indoor temperatures. Due to the absence of a heating mechanism and the inability of AC to counterbalance these thermal losses, widespread discomfort was recorded. RH levels exceeded 80% in some areas, particularly in Zones 2 and 3, creating moisture-related discomfort and increasing the potential for the stability of airborne viruses, a known risk in high-humidity environments.

TC analysis showed that PMV values ranged from -2 to -3, confirming that the occupants experienced severe cold discomfort. The PPD values exceeded 50%, with Zones 2 and 3 experiencing over 90% PPD, meaning that most of the occupants found the environment thermally unsatisfactory. These results indicate that mixed ventilation under extremely cold outdoor conditions was ineffective because NV introduced excessive cooling, while AC was insufficient to maintain thermal balance.

Scenario 2, conducted under milder winter conditions (outdoor temperature = 13°C), showed significant improvements compared to Scenario 1. The air velocity was better distributed (0 m/s to 0.2 m/s), the temperature regulation was more stable (20 °C to 22 °C), and the TC metrics improved significantly (PMV: -1 to 0.8). The improved balance between AC and NV reduced excessive cooling while allowing adequate air exchange.

However, RH levels remained elevated (65% to 75%), particularly in Zones 2 and 3, suggesting that while mixed ventilation improved airflow, it was insufficient for full humidity regulation. High humidity in enclosed spaces is associated with increased airborne virus stability and reduced occupant comfort, highlighting the need for dehumidification strategies or improved air mixing.

PPD values significantly improved (<10%), suggesting that most of the occupants were within acceptable comfort limits. However, above occupant height, PMV values slightly exceeded 0.6 and PPD increased beyond 20%, suggesting localised heat accumulation near the ceiling. These results imply that further adjustments to ventilation rates or enhanced air circulation mechanisms could reduce stratification and improve overall IAQ performance.

Scenario 3, conducted under summer conditions (outdoor temperature = 19°C), exhibited the best overall performance, with:

- Balanced air velocity (0.1 m/s to 0.2 m/s),
- Stable indoor temperatures (20 °C to 22 °C) within ASHRAE-recommended levels, and
- Optimal RH levels (53% to 60%), ensuring improved IAQ and reduced airborne virus stability.

PMV values remained near 0, confirming optimal TC, while the PPD values were consistently $< 10\%$, indicating high occupant satisfaction. The coordinated operation of the AC unit in Zone 2 and the open window in Zone 1 facilitated stable temperature regulation, improved airflow distribution, and improved humidity control.

Unlike Scenario 1, where unregulated cold air infiltration led to excessive cooling and Scenario 2, where humidity levels remained problematic, Scenario 3 provided a well-balanced ventilation strategy. The findings emphasise that a well-designed mixed ventilation system, with controlled window placement and properly calibrated AC operation, is essential to achieve optimal IAQ and TC.

Scenario	**Air Velocity**	**Temperature**	**RH**	**PMV**	**PPD**
1	< 0.02 - 0.4 m/s	< 18 °C	> 70%	-2 to -3	> 70%
2	0.05 - 0.4 m/s	20 °C - 22 °C	65%-75%	-2 to 1.2	> 50%
3	0.05 - 0.4 m/s	21 °C - 23 °C	50% - 65%	-0.5 - 1	10% - 20%

Table 7.3: Comparative summary of scenario performance

7.7 Recommendations for Optimising Mixed-mode Ventilation Performance

Mixed-mode ventilation, which integrates both NV and AC, demonstrated superior performance in this study using the strengths of both systems while mitigating their individual weaknesses. However, to fully optimise its performance, several enhancements should be considered in terms of system control, airflow management, and humidity regulation.

One of the key advantages of mixed-mode ventilation is its ability to dynamically switch between NV and AC modes based on real-time environmental conditions. To maximise this benefit, it is recommended to implement an intelligent ventilation control system that monitors indoor temperature, humidity, CO2 levels, and occupancy patterns. These systems can automatically adjust window openings and humidity control mechanisms to maintain optimal IAQ and TC, while minimising virus transmission.

Airflow balance is crucial in mixed-mode systems, as improper coordination between NV and AC components can lead to excessive ventilation in some zones, while leaving others under-ventilated. This study found that areas near open windows sometimes experienced excessive air velocity (> 0.4 m/s), creating localised discomfort and increasing the risk of viral dispersion. To prevent this, a well-designed airflow distribution strategy should be employed, ensuring that the fresh air intake from NV complements, rather than competes with, the AC air supply. Adjusting the placement of the AC unit and the direction of airflow to work in tandem with open windows can enhance air mixing and prevent thermal stratification.

Humidity control was another challenge observed in mixed-mode ventilation scenarios. Although AC can regulate moisture levels, NV can introduce excess humidity when outdoor RH is high. This study found that RH levels in certain zones occasionally exceeded 70%, which could contribute to the increased stability of the virus and the discomfort of the occupants. To mitigate this, it is recommended to integrate dehumidification units in areas prone to high moisture levels. In addition, automated window controls that close openings when outdoor RH exceeds indoor thresholds can help maintain balanced humidity levels.

Finally, occupant engagement and adaptability are key to maximising the effectiveness of mixed-mode ventilation. Providing building users with real-time feedback on ventilation performance through IAQ monitoring displays or smart building interfaces can encourage optimal window operation and ventilation behaviour. Educating occupants about when to rely on NV versus AC assistance can further enhance the overall performance of the system.

By implementing these recommendations, mixed-mode ventilation can provide an adaptive, efficient, and health-conscious approach to IAQ management, ensuring optimal airflow, stable humidity levels, and superior occupant comfort under diverse environmental conditions.

7.8 Conclusion

This chapter evaluated the effectiveness of mixed-mode ventilation in optimising IAQ, TC, and airborne infection control through CFD simulations. This study examined airflow patterns, temperature regulation, humidity control, TC of the occupant (PMV and PPD), and aerosol dispersion in three distinct hybrid ventilation scenarios. The findings demonstrated that strategically integrating NV and AC can improve air circulation, maintain thermal stability, and reduce airborne virus transmission risks compared to fully AC or fully NV.

The limitations identified in the previous chapters were a key motivation for this study. Chapter 5 (AC system) revealed that fully AC was insufficient in optimising IAQ in all zones because it resulted in stagnation areas and uneven airflow distribution. In contrast, Chapter 6 (NV) showed that fully NV was ineffective in maintaining stable indoor temperatures, leading to thermal discomfort and increased airborne particle transmission. These findings necessitated an investigation into hybrid ventilation systems as a more balanced alternative.

The results indicate that mixed ventilation significantly improved airflow uniformity, reducing stagnation zones while maintaining controlled air circulation. The introduction of AC helped stabilise IAQ and minimise excessive temperature fluctuations that were prevalent in purely NV scenarios. Among the three cases studied, Scenario 3 (summer conditions with an AC in Zone 2 and a window in Zone 1) demonstrated the most balanced performance, providing optimal air distribution, IAQ, and thermal stability. Scenario 2 (winter conditions with moderate outdoor temperatures) performed well but exhibited humidity fluctuations that require further refinement. In contrast, Scenario 1 (cold winter conditions) was the least effective because cold air infiltration and insufficient heating resulted in substantial thermal discomfort.

Regarding virus dispersion, mixed ventilation minimised airborne virus transmission risks by improving air circulation, reducing aerosol retention time, and ensuring that particles were effectively diluted and removed. Compared to fully NV, the combination of AC and natural airflow reduced localised viral accumulation, mitigating the risk of prolonged exposure of the occupant. However, the findings also highlight the importance of ventilation placement because an asymmetric airflow distribution may lead to microclimates within the space, affecting occupant TC and localised IAQ.

This study contributes to existing knowledge by demonstrating that mixed ventilation can provide a more adaptable and effective solution to maintain IAQ and TC in open-plan offices. Previous research has analysed hybrid ventilation in controlled environments, but this study systematically evaluates its performance under real-world seasonal variations. The findings reinforce that adaptive control mechanisms and airflow balancing strategies are essential to maximise the benefits of hybrid ventilation.

Although this study provides a comprehensive evaluation of mixed ventilation performance, certain limitations should be addressed in future research. First, real-time occupant interactions and their impact on airflow dynamics were not included in the CFD simulations, which could introduce additional variability in practical applications. Second, while airflow and IAQ parameters were analysed, energy consumption comparisons were not explicitly evaluated, which remains a crucial consideration for large-scale implementation. Finally, further investigations should explore advanced ventilation control strategies, such as demand-controlled hybrid ventilation, to optimise IAQ while mitigating or minimising virus transmission.

In direct response to Research Question 3 (RQ3), the results demonstrate that mixed-mode ventilation provides an effective solution for improving indoor air quality, ensuring thermal comfort, and reducing airborne infection risks. By combining AC system and natural ventilation, the system overcomes limitations observed in standalone AC and NV strategies such as stagnation zones, thermal discomfort, and uncontrolled aerosol dispersion.

Regarding Research Question 4 (RQ4), this chapter highlights how hybrid ventilation can be configured and adapted under varying seasonal and environmental conditions to optimise indoor environmental quality. Specifically, the configuration used in Scenario 3 (summer conditions with AC and window ventilation) was found to be the most effective, offering a balanced approach to airflow regulation, temperature control, and aerosol dilution, thereby supporting a more resilient and adaptable ventilation framework.

This chapter contributes to the growing body of research on hybrid ventilation by providing a detailed computational evaluation of mixed-mode strategies in a real-world office context. Through CFD simulations under seasonal conditions, the chapter identifies the optimal configurations that balance airflow, temperature regulation, humidity control, and airborne infection risk mitigation. The findings extend the understanding of how hybrid systems can address the limitations of standalone AC and NV solutions, offering practical guidance for designing energy-efficient, health-conscious ventilation strategies in modern workspaces.

In conclusion, Scenario 3 demonstrated the best overall performance, confirming that a well-designed mixed-ventilation strategy can significantly improve IAQ, reduce airborne virus transmission risks, and ensure occupant TC. These findings provide valuable information for the design and optimisation of hybrid ventilation systems, supporting the development of healthier and more efficient indoor environments. Future research should focus on adaptive ventilation strategies that dynamically respond to environmental conditions and occupancy levels, further enhancing the practicality and efficiency of mixed-mode ventilation systems.

Chapter 8

Conclusion

This thesis has systematically investigated the effectiveness of different ventilation strategies (i.e., air conditioning (AC), natural ventilation (NV), and mixed-mode ventilation) in controlling indoor air quality (IAQ), thermal comfort (TC), and airborne infection risks in an open-plan office environment. By integrating Computational Fluid Dynamics (CFD) simulations with real-world environmental monitoring, this research has provided critical insights into airflow dynamics, pollutant dispersion, and thermal regulation under varying ventilation conditions. The findings offer practical guidance for designing healthier indoor environments, particularly in the context of post-pandemic ventilation strategies.

8.1 Revisiting Research Questions and Key Findings

This research aimed to answer four key research questions that guided the methodological approach and analysis of the study, particularly with respect to ventilation performance, thermal comfort, and the risk of airborne virus transmission. Each research question is addressed in detail below, linking the findings of the relevant chapters and ensuring the implications for viral infection mitigation are clearly articulated.

8.1.1 Research Question 1: How do viral particles transmit within indoor environments and what factors influence their transmission dynamics?

The first research question was explored in Chapter 2 through a systematic review of the literature, which highlighted the key mechanisms influencing airborne transmission of respiratory viruses. The findings underscore the complexity of airborne virus transmission in indoor environments, with aerosol dispersion being influenced by factors such as air circulation, humidity levels, temperature, and ventilation effectiveness.

The review demonstrated that respiratory viruses can remain viable in airborne particles for extended periods, with transmission risks increasing in poorly ventilated spaces. Evidence suggests that inadequate ventilation leads to higher aerosol retention times, increasing the risk of exposure to occupants. Computational studies further revealed that airflow patterns play a critical role in viral dispersion, with high-velocity air currents potentially exacerbating the spread of infectious aerosols. The findings confirmed the necessity of strategic airflow management to prevent stagnation zones, where viral aerosols may accumulate and persist.

This study highlights the importance of integrating ventilation strategies that balance air distribution with effective pollutant removal. The use of CFD simulations has proven valuable in identifying high-risk areas for viral accumulation, reinforcing the role of computational modelling in optimising IAQ management strategies. These insights underscore the necessity of airflow optimisation not only for comfort but also for reducing airborne infection risk, highlighting that viral transmission must be considered a central factor in indoor ventilation design.

8.1.2 Research Question 2: Can CO2 levels serve as reliable indicators to assess IAQ and signal the potential risk of airborne infections in office environments?

Chapter 4 addressed the second research question by evaluating the correlation between CO2 levels and IAQ parameters in the teaching office environment. The analysis revealed that CO2 concentrations consistently exceeded the recommended threshold of 700 ppm during peak occupancy periods, aligning with increased risks of airborne infection due to poor ventilation.

The study confirmed that CO2 serves as a useful proxy for ventilation effectiveness, as high concentrations indicate inadequate air exchange. This finding supports the adoption of real-time CO2 monitoring as an early warning system for ventilation deficiencies. Since elevated CO2 levels often correlate with exhaled breath accumulation, they can serve as indirect indicators of increased viral particle concentration, further reinforcing their value in infection risk monitoring.

However, the study also acknowledged the limitations in using CO2 as an independent IAQ indicator. While elevated CO2 levels suggest insufficient ventilation, they do not directly measure pathogen concentrations or pollutant accumulation. As a result, a multiparameter approach is recommended, incorporating temperature, humidity, and particulate matter monitoring, to provide a comprehensive IAQ assessment.

8.1.3 Research Question 3: What ventilation strategies can be implemented to minimise the risk of airborne infections in office environments?

This question was comprehensively addressed in Chapters 5, 6, and 7, where three ventilation systems AC, NV, and mixed-mode ventilation were comparatively evaluated.

Chapter 5 established the baseline performance of a typical four-way ceiling cassette AC system. Although maintaining acceptable temperature ranges and moderate airflow in the core zones, it also revealed significant limitations, including stagnant zone formation, uneven air distribution, and indoor air recirculation, which elevated the risk of aerosol accumulation and cross-contamination.

Chapter 6 expanded the analysis to NV systems. While NV particularly CV proved highly effective in pollutant dilution and increasing air change rates under favourable conditions, it was hindered by outdoor environmental variability. Low air exchange during stagnant weather undermined its reliability. Nonetheless, NV emerged as a viable infection mitigation tool when conditions permitted, especially in buildings with operable windows and adaptive use protocols.

Finally, Chapter 7 introduced mixed-mode (hybrid) ventilation as a balanced solution. By combining the strengths of NV and AC, this strategy demonstrated improved airflow uniformity, enhanced pollutant removal, and greater control over temperature and humidity. Scenario 3 (AC in Zone 2 + open window in Zone 1) emerged as the most effective configuration in terms of IAQ, thermal comfort, and virus mitigation metrics. This chapter confirmed that integrated ventilation strategies, rather than isolated systems, are better suited to support occupant health in dynamic indoor settings. The comparative analysis confirmed that engineering solutions must prioritise not only air distribution and comfort but also targeted virus mitigation strategies to reduce transmission risk in real-world conditions.

8.1.4 Research Question 4: How can ventilation systems be configured to maintain a good IAQ, ensure TC, and reduce virus dispersion in the office environment?

Research Question 4 focusses on the configuration and optimisation of ventilation systems and was explored primarily through Chapters 6 and 7. These chapters went beyond evaluation by simulating different configurations, airflow placements, and seasonal variations to identify actionable setup strategies.

Chapter 6 illustrated how NV strategies such as cross-ventilation can be spatially and temporally adjusted to meet seasonal IAQ needs. The analysis demonstrated that strategic window opening configurations, adjusted WWR, and placement of occupants relative to openings significantly impacted both IAQ and thermal satisfaction. However, it also highlighted that relying solely on NV introduces uncontrolled variability, which limits its standalone applicability.

Chapter 7 addressed these shortcomings by configuring mixed-mode systems to deliver controlled and stable performance in both summer and winter conditions. Among the three setups tested, Scenario 3 was the most effective due to its balance of air distribution, thermal regulation, and humidity control. These findings provide strong evidence that hybrid systems, when properly configured, offer the most promising pathway to achieve both infection risk reduction and occupant comfort.

The chapter concluded with design recommendations that include optimising airflow directions, integrating smart control systems, and continuously monitoring IAQ metrics to dynamically respond to occupancy and weather changes. Ultimately, the optimal configuration of ventilation systems must integrate virus control measures, such as minimising particle suspension and enhancing pollutant removal pathways, particularly in shared spaces with fluctuating occupancy. These configuration strategies directly respond to the requirements of Research

Question 4.

8.2 Implications for Building Design and Operation

The findings of this research have critical implications for current and future practices in the Architecture, Engineering, and Construction (AEC) sector. The increasing demand for resilient, health-focused, and energy-efficient indoor environments—especially in the post-pandemic era—calls for scalable and adaptable ventilation strategies. This study demonstrates that mixed-mode ventilation offers a robust solution by combining the control of mechanical systems with the flexibility of natural ventilation. Although this research focused on a teaching office at Cardiff University, the underlying methodology and simulation framework are readily transferable to other building typologies, including schools, hospitals, and commercial spaces, each with unique occupancy profiles and ventilation challenges.

For building designers, engineers, and facility managers, this research underscores the importance of prioritising flexibility in ventilation design. Strategies such as integrating operable windows, variable dampers, demand-controlled systems, and ceiling fans can help tailor airflow patterns to seasonal and occupancy variations. These configurations also support adaptability across diverse regional climates and architectural forms.

Moreover, real-time monitoring using advanced sensor networks for CO2, temperature, humidity, and particulate matter is essential for dynamically assessing IAQ and adjusting ventilation in response to actual conditions. The incorporation of smart, data-driven control systems enables buildings to respond more efficiently to occupant presence and environmental changes, paving the way for truly intelligent indoor environments.

From a human-centric perspective, the research highlights the integral role of occupant comfort, wellbeing, and behavioural adaptation in the success of ventilation strategies. Thermal satisfaction, perceived air quality, and trust in the system directly affect acceptance and use. Therefore, future implementations must go beyond technical performance and consider psychological and social dimensions—ensuring systems are intuitive, responsive, and user-friendly.

Finally, these findings support broader sustainability and public health goals. By promoting energy-efficient solutions that also reduce airborne infection risk, this research contributes to emerging standards for healthier indoor environments. It encourages the AEC sector to adopt holistic, resilient approaches that integrate environmental responsibility, socio-cultural responsiveness, and economic viability—fostering healthier, more inclusive, and adaptable buildings for diverse populations and future challenges.

8.3 Comparison of Mixed-mode Ventilation Against Natural Ventilation and Air Conditioning

Mixed-mode ventilation combines NV and AC to leverage the strengths of both systems, while mitigating their individual weaknesses. This approach aims to improve airflow distribution, stabilise temperature fluctuations, regulate humidity, and improve overall IAQ. The results of this study indicate that mixed-mode ventilation outperformed both NV and the AC system in achieving optimal indoor environmental conditions.

In terms of airflow distribution, mixed-mode ventilation provided a more balanced and effective air movement pattern, reducing stagnation zones that were prevalent in both NV and AC scenarios. In Scenario 3, which was conducted under summer conditions, air velocity remained stable between 0.1 m/s and 0.2 m/s, significantly minimising dead zones in Zones 2 and 3. In contrast, NV alone resulted in highly variable airflow patterns, with certain areas experiencing excessive air movement while others suffered from stagnation. While the AC system was more consistent, it showed stagnant zones in corners and areas blocked by furniture, limiting air mixing. The combination of AC and NV in mixed mode scenarios improved airflow uniformity and reduced localised ventilation deficiencies.

Temperature regulation was also more stable under mixed-mode ventilation. The combined use of NV and AC cooling prevented the overheating observed in NV scenarios while eliminating the over-cooling effects present in AC-only settings. Scenario 3 demonstrated the most balanced temperature range, maintaining indoor conditions between 20 °C and 23 °C, which is well within the recommended levels of ASHRAE. In comparison, NV often caused temperature variations in different zones, while AC created cold air pockets near air supply vents. The PMV values in mixed-mode ventilation remained close to 0, confirming an optimal balance of TC, whereas NV exhibited PMV values exceeding 0.5 in stagnant zones, and AC occasionally caused over-cooling discomfort.

Humidity control was another area where mixed-mode ventilation proved to be superior. Unlike NV, which allowed RH to fluctuate with outdoor conditions, and AC, which lacked sufficient dehumidification in certain areas, mixed-mode ventilation effectively regulated indoor moisture levels. In Scenario 3, RH remained between 53% and 60%, which is well within the comfort recommendations of ASHRAE. This was a significant improvement over NV, where RH frequently exceeded 65% and AC, sometimes resulting in elevated indoor moisture levels. The introduction of fresh air through NV helped dilute indoor contaminants, while AC contributed to stable humidity regulation.

In general, mixed-mode ventilation achieved a more balanced approach to IAQ management, outperforming both NV and AC in airflow distribution, temperature regulation, and humidity control. It effectively mitigated the stagnation issues associated with NV while addressing the air recirculation concerns of AC. This hybrid approach ensures a healthier and more comfortable indoor environment by maintaining optimal ventilation effectiveness, stable thermal conditions, and regulated humidity levels.

To further optimise mixed-mode ventilation, adaptive control systems that adjust window openings and AC airflow based on real-time IAQ and TC metrics could be implemented. Furthermore, strategic placement of windows and vents could enhance cross-ventilation while preventing excessive airflow near occupants. Integrating dehumidification systems would further stabilise RH levels, particularly in humid climates. The use of air filtration, such as HEPA or MERV filters, within the AC system could also help reduce indoor pollutant concentrations, improving air quality while maintaining energy efficiency.

In conclusion, mixed-mode ventilation presents the most effective solution to achieve optimal IAQ and TC in indoor environments. By integrating NV and AC, this approach maximises the benefits of both systems, providing superior airflow distribution, temperature stability, and humidity control. Its ability to regulate fresh air intake while ensuring controlled air circulation makes it a highly suitable strategy for improving indoor environmental conditions and occupant well-being.

8.4 Limitations

While this research has produced valuable insights into the performance of AC, NV, and mixed-mode ventilation strategies in office settings, several limitations should be acknowledged:

- **Static occupancy modelling:** The CFD simulations assumed static occupants and fixed heat loads. In real-world scenarios, occupant movement, varied breathing rates, and behavioural diversity can significantly influence airflow and pollutant dispersion. This simplification may affect the accuracy of dynamic exposure assessments.

- **Single building type and location:** The study was confined to a teaching office at Cardiff University. While the seasonal scenarios enhance contextual realism, the findings may not directly generalise to other building typologies, such as schools, hospitals, or commercial centres, which have different ventilation demands and occupancy patterns.

- **Limited validation scope:** Although the model was validated against literature and monitoring data, the availability of high-resolution spatiotemporal field data limited deeper validation for transient airflow or virus concentration distributions.

- **No direct pathogen modelling:** The study relied on proxy indicators like CO_2 and PM, but did not simulate specific viral particle survivability or viability under varying humidity or UV light levels.

- **Exclusion of energy consumption modelling:** While thermal comfort and IAQ were addressed, the energy demands of ventilation configurations — especially mixed-mode systems — were not evaluated, limiting sustainability insights.

8.5 Future Research Directions

Building upon the limitations and findings of this thesis, several future research avenues are proposed:

- **Dynamic occupancy and behaviour simulation:** Future studies should incorporate dynamic occupancy schedules, metabolic rate variations, and movement pathways using real-time sensors or agent-based models to improve the realism of IAQ predictions.

- **Multi-building, multi-climate assessments:** Expanding the methodology to diverse building types (e.g., classrooms, healthcare facilities) and climate zones will help generalise the findings and guide location-specific ventilation strategies.

- **Energy and cost performance integration:** Future work should assess the energy efficiency and lifecycle cost of hybrid ventilation systems using building energy simulation tools, allowing trade-off analyses between IAQ, comfort, and energy use.

- **Integration of viral viability models:** Coupling CFD with virology-informed decay or inactivation models (e.g., based on RH, temperature, and UV exposure) can improve predictions of infection risk and pathogen persistence.

- **Development of AI-enabled smart ventilation systems:** Leveraging machine learning and IoT sensor networks can enable real-time optimisation of ventilation settings, adapting to occupancy, IAQ trends, and outdoor conditions dynamically.

- **Field studies and human-centred validation:** Real-world implementation of mixed-mode systems with occupant feedback, sensor logging, and health data would provide holistic validation and practical guidance for scalable deployment.

- **Broader adaptability and impact assessments:** Future research should explore environmental sustainability (e.g., carbon footprint and energy consumption of ventilation systems), socio-cultural influences (e.g., local behaviours and acceptance of natural ventilation), and economic implications (e.g., cost-benefit analyses of hybrid systems). These aspects are critical for ensuring scalable, inclusive, and policy-relevant applications across varied regional and building contexts.

8.6 Final Reflections

Although this thesis focused on a specific office setting at Cardiff University, the methodology and simulation framework were designed to explore ventilation strategies, particularly natural and mixed-mode ventilation, across multiple seasonal conditions. By evaluating performance under both winter and summer scenarios, the research demonstrates how environmental context influences airflow dynamics, thermal comfort, and infection risk. While the results are location-specific, the broader modelling approach and analytical methods are adaptable and can be applied to other building types, climates, or occupancy patterns. This adaptability makes the study a valuable reference for future ventilation research and for practitioners aiming to optimise IAQ and occupant comfort in varied settings.

Crucially, this research confirms that indoor air quality, thermal comfort, and airborne virus transmission are deeply interconnected. Poor ventilation not only degrades comfort but also increases the concentration and persistence of airborne pathogens. The integrated evaluation of these three factors is therefore essential for designing safe, comfortable, and health-resilient indoor environments.

This thesis makes several significant contributions to the field of indoor environmental quality and ventilation engineering. First, it provides a comprehensive CFD-based framework for assessing the impact of various ventilation strategies AC systems, natural ventilation, and mixed-mode ventilation on indoor air quality, thermal comfort, and airborne infection risk. Second, the study presents an integrated methodology that combines real-world monitoring with advanced numerical simulations to evaluate performance across realistic seasonal conditions.

Third, it introduces scenario-based evaluations that highlight both the strengths and limitations of each strategy, offering practical insights for optimising ventilation design in office environments. Finally, the thesis contributes to current knowledge by demonstrating the effectiveness of hybrid ventilation systems in achieving a balanced approach to infection mitigation and occupant comfort, laying the groundwork for future smart, adaptive ventilation systems in post-pandemic building design.

A comparative analysis across the chapters revealed that no single ventilation strategy is universally optimal. AC systems provide thermal stability but often lead to stagnant zones and recirculated air, reducing ventilation efficiency. NV enhances air change and pollutant dilution but lacks climate control and consistency. Mixed-mode ventilation emerged as the most balanced solution especially in Scenario 3, which is successfully combining natural airflow with AC to maintain stable IAQ, reduce airborne transmission risk, and support thermal comfort. The study also identified several optimisation strategies: controlling window opening ratios, maintaining air velocity below 0.2 m/s to limit aerosol spread, managing RH under 60%, and placing AC outlets to complement natural airflow paths. These findings form a practical framework for tailoring ventilation setups to diverse indoor environments.

This thesis has demonstrated that mixed-mode ventilation provides a viable and effective strategy to optimise IAQ, improve thermal comfort, and mitigate the risks of airborne infection in office environments. By integrating natural ventilation with AC, this research contributes to the ongoing discourse on sustainable and health-focused building design. The findings advocate for a paradigm shift in ventilation strategies, emphasising adaptability, real-time IAQ monitoring, and energy-efficient solutions.

As urban environments continue to evolve, future research should focus on developing intelligent and responsive ventilation systems that dynamically adjust to environmental conditions. Through interdisciplinary collaboration, these insights can contribute to the development of next-generation building regulations and ventilation standards, ultimately shaping healthier and more resilient indoor environments for generations to come.

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