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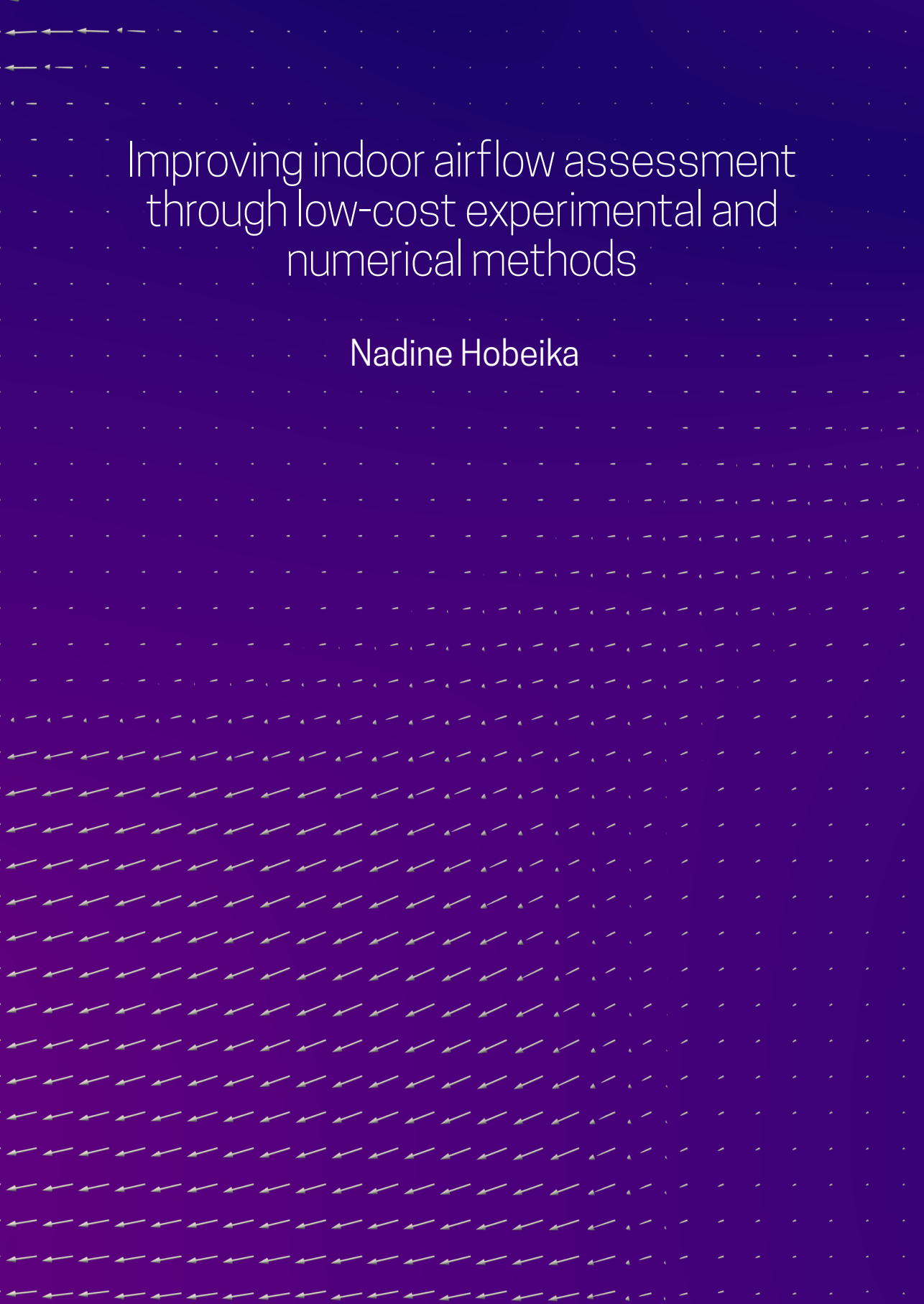
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Improving indoor airflow assessment through low-cost experimental and numerical methods

Nadine Hobeika

Improving indoor airflow assessment through low-cost experimental and numerical methods

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Improving indoor airflow assessment through low-cost experimental and numerical methods

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to be defended publicly on
Monday 07 September 2026 at 10.00 o'clock

by

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Contents

Acknowledgments	vii
1 Introduction	1
1.1 Context	1
1.2 Problem statement	3
1.3 Research questions and scope	6
1.4 Outline of the thesis	7
2 Background	9
2.1 Turbulent free jet flows - in theory	10
2.2 Indoor turbulent free jets - in practice	12
2.3 Conclusion	19
3 Milou	21
3.1 Introduction	22
3.2 Methodology	23
3.3 Results and discussion	32
3.4 Limitations and future work	42
3.5 Conclusion	43
4 Exploring the impact of Reynolds-Averaged Navier-Stokes solvers	45
4.1 Introduction	46
4.2 Experimental and Numerical Methods	47
4.3 Results	60
4.4 Conclusion	69
5 The devil is in the details	71
5.1 Introduction	72
5.2 Methods	74
5.3 Results and discussion	81
5.4 Conclusion	94
6 Conclusions and Future Work	97

Contents

6.1	Answer to the research subquestions	98
6.2	Answer to the main research question and overall discussion . . .	100
6.3	Limitations and Future Work	101
A	Milou: supporting material	103
A.1	Open-source deliverables and list of main electrical components .	103
A.2	Computational Fluid Dynamics (CFD) representation of the air- flow in the test chamber	104
B	The devil is in the details: supporting material	107
B.1	Furniture simplification proof-of-concept implementation	107
B.2	Temperature and passive scalar concentration	108
	Bibliography	113
	Summary	133
	Samenvatting	135
	Résumé	137
	ملخص	139
	Curriculum Vitae	141

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Nadine Hobeika

Dublin, Ireland - April 2026

1 Introduction

1.1 Context

A building should not kill its residents. This fundamental building design principle was first introduced nearly 4000 years ago in Hammurabi's Code (translated in [Harper \[1904\]](#)) to ensure the structural integrity of a building. Today, it also extends to other important aspects of building performance, such as energy-efficient ventilation, fire safety, and even physical and psychological well-being inside a building [[Ashrae, 2019](#); [REHVA, 2020](#); [U.S. Green Building Council, 2013](#)]. To better achieve these building performance goals, the CIB W60 Commission [[Gibson, 1982](#)] formally introduced the concept of performance-based building design (PBBD) as a modern approach to achieving optimal building performance. PBBD focuses on achieving specific, measurable performance goals - such as thresholds for energy consumption, structural load capacity, or occupant thermal comfort - through innovative and flexible design solutions rather than rigid adherence to prescriptive code requirements [[Gibson, 1982](#)] (See [Figure 1.1](#)). However, PBBD has been primarily applied to enhance structural resilience [[Filiatrault et al., 2021](#); [Gernay, 2024](#)] and reduce energy consumption [[Echenagucia et al., 2015](#); [European Parliament and Council of the European Union, 2024](#); [Gassar et al., 2021](#); [Hamdy et al., 2016](#)], while other aspects of building performance, particularly healthy indoor ventilation, remain underexplored, limiting our understanding of PBBD's potential for promoting occupant health and indoor air quality [[Becker, 2008](#); [Guyot, 2018](#); [Poirier et al., 2023](#)].

Healthy indoor ventilation has emerged as an important performance criterion for buildings, as the limitations of current ventilation designs became evident during the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) pandemic [[Morawska et al., 2021](#)]. Despite existing laws, regulations, codes, and standards related to ventilation [[Ashrae, 2019](#); [Mathisen et al., 2004](#); [Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2020](#)], many buildings fail to effectively mitigate the airborne transmission of deadly viruses [[Bluyssen, 2014](#); [Morawska et al., 2024](#); [Qian and Zheng, 2018](#); [Zhang et al., 2024b](#)]. The lack of effective mitigation measures against deadly viruses is partially due to the prescribed ventilation requirements that unrealistically assume uniform air distribution throughout a room. For instance, the design and placement of airflow

1 Introduction

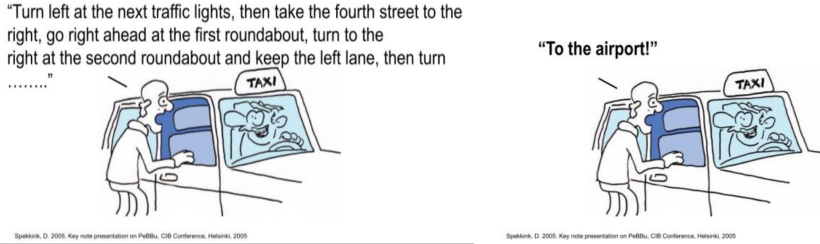


Figure 1.1: Illustration of a prescriptive approach (on the left) compared to a performance-based approach (on the right) from [Spekkink \[2005\]](#) in [Guyot \[2018\]](#).

supply and exhaust vents, or the placement of furniture, can both meet regulatory requirements while creating zones with poor ventilation that promote airborne transmission [[Morawska et al., 2021](#)]. This illustrates that ventilation design can fail if the effective distribution of airflow to ensure that the occupied space receives sufficient ventilation is not properly considered.

Moreover, in current architectural practices, integrating ventilation into buildings, especially mechanical ventilation, is done only after the design process is complete, because it is regarded as an engineering rather than a design problem [[Sundell et al., 2021](#)]. This can lead to suboptimal integration of ventilation systems within the overall building design, compromising their effectiveness and alignment with health-based performance goals. To achieve these health-based goals, the building’s ventilation effectiveness should be assessed at both the design and post-construction stages [[Becker, 2008](#); [Guyot, 2018](#)].

To this end, this thesis proposes low-cost experimental and numerical methods to enable better integration of ventilation assessment at different stages of a building’s life cycle (see [Figure 1.2](#)). During the design stage, computational fluid dynamics (CFD) simulations are used to predict ventilation airflow and respiratory jets in a room, and to iterate on different design solutions to select the optimal solution. These simulations require initial boundary conditions and a 3D model of the ventilated space, and must be validated at the design assessment stage. After the building has been constructed (the built stage), especially in occupied buildings, ventilation performance assessment in a room requires on-site measurements and monitoring of indoor air quality (IAQ) indicators, such as airflow velocity, temperature, relative humidity, and particulate matter (PM). The data from these measurements can be used both to assess the effective ventilation performance of the final built product and to validate the ventilation performance of future buildings at the design stage (see [Figure 1.2](#)). Making ventilation assessment methods more accessible allows for a safer indoor

environment that does not kill its residents.

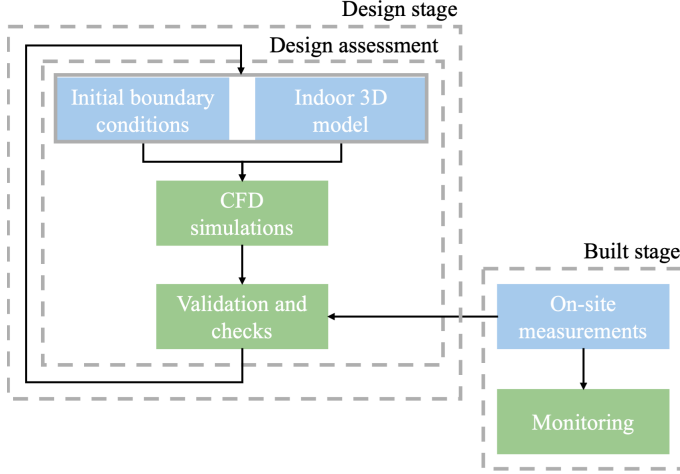


Figure 1.2: Performance-based assessment approach of indoor ventilation at different stages of a building's life cycle.

1.2 Problem statement

The implementation of a performance-based design assessment requires first determining which indicators to use as performance criteria and second, which assessment methods to use to measure or predict those indicators. Previous work has identified suitable performance criteria for different ventilation-based PBBDs [Becker, 2008; Guyot, 2018]. However, no work has been done to make the assessment methods more accessible across the building's life cycle. These assessment methods face two challenges when it comes to PBBD:

1. The assessment methods used to evaluate ventilation performance require a multidisciplinary approach comprising CFD numerical expertise, measurement techniques, and 3D modelling.
2. These assessment methods can be time- and resource-intensive, making them unrealistic to apply to the design process or post-construction.

Therefore, in this thesis, I investigate and propose experimental and numerical assessment methods that enable a more manageable, less costly, yet reliable, adoption of a performance-based approach to healthy indoor ventilation during

1 Introduction

the design and post-construction phases at the room level. To achieve this, I consider the following three challenges:

Challenge 1 *On-site measurements are costly both in resources and manual labour. Continuously measuring ventilation-related indicators requires low-cost, low-effort, high-accuracy techniques to assess the performance criteria.*

To assess the ventilation performance of the occupied building, on-site measurements provide data under realistic conditions, avoiding scaling effects and numerical model assumptions. IAQ indicators, such as airflow velocity, temperature, humidity, and PMs, provide insights into airflow patterns and pollutant concentrations. Measuring and monitoring these indicators can help identify when and where ventilation fails to provide sufficient air to dilute and extract pollutants, or to regulate air temperature and relative humidity, enabling timely adjustments to maintain a healthier indoor environment. Additionally, these measurements provide data to validate CFD simulations. Validation ensures the reliability and accuracy of these simulations by comparing simulation results with measured data and evaluating how well the model matches the measurements.

Typically, point-wise measurements - measurements at discrete points in space - are used to continuously measure performance indicators indoors. However, traditional measurement techniques rely on an expensive, dense network of stationary sensors placed at fixed locations within a room, often positioned on walls or ceilings rather than in areas where occupants are most affected. These methods might alternatively require significant manual labour to move sensors around when not enough sensors are available. While these measurements provide useful data on overall air quality, they still do not accurately capture local variations, particularly in occupants' breathing zones. The limitation of stationary sensors on walls or ceilings stems from the highly uneven airflow distribution, with factors such as furniture influencing air movement. As a result, measurements from stationary sensors, whether distant or poorly placed, may not reflect the actual air quality individuals experience, leading to an incomplete or misleading assessment of ventilation performance.

Challenge 2 *CFD simulations employ different solvers with different assumptions to model the same indoor airflow from ventilation and respiratory activities. Iterating over different design solutions to optimise indoor airflow patterns requires balancing computational cost and accuracy of the results.*

CFD simulations are used to test and optimise the ventilation performance of the final design solutions. These simulations can accurately model indoor airflow and contaminant transport, providing insights into indoor flows that can help reduce airborne transmission. By numerically resolving the Navier-Stokes equations, CFD simulations can predict airflow patterns, including recirculation

regions, a breathing jet, and thermal stratification, as well as the concentration and dispersion of respiratory particles. Resolving the Navier-Stokes equations involves using solvers that rely on assumptions to simplify the complex, real-world dynamics of indoor flows. These assumptions include:

1. the (in)compressible nature of the flow - are density variations small enough to ignore?
2. the (un)steadiness of the flow - is the time-dependent component important for the prediction needed?
3. turbulence modelling - how much of the turbulence should be modelled?
4. thermal properties - are temperature variations small enough to ignore?
5. boundary conditions - should the inlet profiles be uniform or not?
6. grid modelling - which part of the domain is of interest and requires more refinement?

However, these assumptions are user-dependent, and therefore, the choice of assumptions and, consequently, the choice of CFD solvers can vary even when modelling the same indoor flows. Using different CFD solvers on the same indoor problem can yield different results in airflow patterns and predictions for other indicators. Even codes that in principle solve the same equations with the same assumptions can differ in implementation and yield different results [Peng et al., 2016; van Hooff et al., 2018]. Additionally, these assumptions can significantly increase the computational cost of CFD simulations, making "cheaper" assumptions more practical for optimisation at the expense of lower accuracy. Understanding how these assumptions affect indoor flow predictions would better inform users about the costs and accuracy of the solvers they choose, making decision-making less arbitrary.

Challenge 3 *There is no clear understanding of the impact of the geometric level of detail of furniture on the predicted airflow patterns.*

The computational domain for a CFD simulation for ventilation assessment is a 3D model of a room or several rooms. These models approximate the actual or planned indoor environment by incorporating the geometry details that represent the room's spatial characteristics. The indoor geometric level of detail (LOD) of these models represents the degree to which geometric features, such as walls, furniture, and openings, are included. When it comes to ventilation, furniture plays an important role in defining airflow patterns because it acts as an obstacle in the room. A higher furniture LOD (fLOD) may provide more accuracy in terms of realism but demands more computational resources, while a lower fLOD might oversimplify the computational domain. The selection of an appropriate

1 Introduction

fLOD depends on the model's intended use, the acquisition techniques and the simulation resources available.

While some indoor LOD frameworks exist [[Apple Inc. and Open Geospatial Consortium, 2021](#); [Open Geospatial Consortium, 2012, 2020, 2021](#); [Tang et al., 2018](#)], they are mainly intended for indoor navigation applications where furniture detail does not capture the different ways furniture can be modelled in ventilation applications. A lack of understanding of the required fLOD could lead to erroneous conclusions about the effectiveness of certain ventilation solutions or to additional computational costs that would discourage the assessment of ventilation during the design stage. Ideally, the fLOD should be determined based on application goals, balancing resource use (time and costs) with maximising simulation accuracy. Additionally, the lack of a clear and detailed definition of fLOD for ventilation limits the proper comparison of ventilation performance between modelled predictions and measured data from the post-construction stage.

1.3 Research questions and scope

The aim of this thesis is to investigate low-cost, accurate numerical and experimental methods for assessing the effectiveness of indoor ventilation, thereby making a ventilation-based robust PBBD more achievable. The assessment methods are proposed for the design and post-construction stage of a building's life cycle. Therefore, the main research question of this thesis is:

Can low-cost numerical and experimental methods accurately and robustly assess indoor ventilation performance [at different stages of a building's life cycle]?

- Sub-question 1: How do current experimental and numerical practices and assumptions impact indoor and respiratory airflow predictions?
- Sub-question 2: How can point-wise indoor measurements be automated through a low-cost approach that reduces interference with the surrounding airflow during the measurements?
- Sub-question 3: Which CFD solver has the best cost-to-applicability compromise to support ventilation-based design optimisation?
- Sub-question 4: What is a suitable fLOD definition for indoor ventilation applications, and what is the impact of furniture levels of detail?

1.3.1 Scope

The aim of the proposed methods in this thesis is to optimise the time, cost, and effort required to assess ventilation performance without compromising the quality of the process. This work does not provide an optimal ventilation design solution, but rather focuses on how to approach such solutions from a healthy ventilation perspective. Additionally, this thesis focuses on mechanical ventilation; natural ventilation is out of scope. Moreover, the health goal I focus on is reducing airborne transmission; therefore, I use indicators related to airborne transmission, such as airflow velocity, temperature, relative humidity, and aerosol concentration. However, the assessment methods I propose can easily be applied to different indicators if needed. Finally, the numerical methods proposed in this thesis are based on physics-based airflow modelling to improve the efficiency of ventilation performance assessments. Although data-driven approaches have recently emerged as promising techniques for reducing computational cost, they typically require training data and are beyond the scope of this work.

1.4 Outline of the thesis

This thesis consists of 6 chapters as follows:

- Chapter 2 introduces the reader to the free turbulent jet and its application to indoor ventilation and breathing jets. The chapter also presents the available low-cost experimental and numerical methods for studying indoor ventilation and breathing jets. This chapter addresses sub-question 1 of this thesis and introduces the necessary theoretical and methodological background and concepts to support the subsequent chapters. Each subsequent chapter will contain a more specific literature review to support the aim of that chapter.
- Chapter 3 is dedicated to the design and validation of a line-following robot that automates mobile on-site measurements for ventilation assessment. Special attention is given to demonstrate the robot's low interference with the surrounding airflow by deploying it in a controlled laboratory setting. The findings of this chapter help answer sub-question 2 of this thesis.
- Chapter 4 presents the most commonly used Eulerian-Eulerian solvers in ventilation studies. It also provides validation of those solvers using measurements conducted with the robot from Chapter 3 and from the literature, and evaluates their suitability for studying indoor ventilation and breathing jets. The results presented in this chapter contribute to answering sub-question 3 of this thesis.

1 Introduction

- Chapter 5 proposes a definition of the furniture level of detail and demonstrates its impact on airflow patterns. The chapter shows how various fields and ventilation regimes are impacted by the furniture level of detail. This chapter provides findings that address sub-question 4 of this thesis.
- Chapter 6 presents the answers to the research questions posed in Chapter 1, as well as the scientific contributions and limitations of this thesis. It also offers recommendations for future research on low-cost, performance-based assessment methods related to indoor ventilation and breathing jets.

Chapter 2 is based on a published scientific paper [Hobeika et al., 2023a]. Chapter 4 is based on two conference abstracts [Hobeika et al., 2023b, 2026a]. Chapter 5 is based on a conference abstract [Hobeika et al., 2025a].

2 Background

This chapter introduces the key concepts behind breathing and ventilation jets and how they shape the surrounding indoor airflow. It starts by explaining the theory behind free turbulent jets and connects to breathing and ventilation jets. The chapter then focuses on low-cost assessment methods that validate the theory and provide further insight into where, how, and why these jets differ from the theory in practice. These assessment methods are divided into two categories: experimental measurements and computational fluid dynamics and numerical simulations. The chapter explains which low-cost methods are used for each category and provides practical examples of their application in the literature.

Parts of this chapter are based on the following paper:

Hobeika, N., García-Sánchez, C., & Bluyssen, P. M. (2023). Assessing Indoor Air Quality and Ventilation to Limit Aerosol Dispersion—Literature Review. Buildings, 13(3), Article 742. <https://doi.org/10.3390/buildings13030742>

2 Background

Breathing is the only continuous expiratory activity when compared to speaking, coughing and sneezing. While it provides the necessary air for the survival of any individual, breathing also plays an important role in indoor airborne transmission, which is the spread of infectious agents through aerosols suspended in the air. Consequently, breathing is generally considered a multiphase turbulent free jet, with the airflow as the continuous phase and aerosols as the discrete phase. The characteristics of the breathing jet are affected, on the one hand, by intrinsic human characteristics such as the mouth opening area, the time-dependent expired flow rate, and the temperature and relative humidity at the mouth, and on the other hand, by the surrounding airflow characteristics, such as the direction of the dominant flow, the ambient temperature, and the relative humidity (RH). In fact, in the presence of mechanical ventilation, the surrounding airflow is also determined by a different type of turbulent free jet emanating from the ventilation inlet. These ventilation inlet jets are also affected by intrinsic characteristics, such as inlet temperature and RH, as well as by ventilation system characteristics, such as inlet area, airflow rate, and inlet location.

2.1 Turbulent free jet flows - in theory

A turbulent free jet is a free shear flow created when a fluid at some velocity exits an opening into a large body of the same or another fluid, often at rest, where Reynolds number is high enough that the jet flow is turbulent [Pope, 2000]. The jet is not confined by solid boundaries and spreads and entrains surrounding fluid due to turbulence [Pope, 2000]. There are several types of turbulent free jets such as axisymmetric round (3D) and planar (2D) free jets depending on the shape of the opening from where the jets emanate. In free turbulent jets, the flow along the axial direction is divided into four regions (see Figure 2.1), as follows:

1. the potential core region
2. the interaction (transition) region
3. the fully-developed region
4. the terminal region

The regions' division is based on the nondimensional distance x/d , where x is the downstream distance from the opening and d is the characteristic opening size (diameter for a round jet or slot width for a plane jet or the square root of the area of the opening). The potential core region occupies the near field and is defined by a uniform centreline velocity equal to the exit velocity, indicating limited entrainment of ambient fluid. The transition region is where the shear layers grow and interact with the ambient surrounding fluid. Here, turbulence intensifies, leading to the onset of centreline velocity decay. The velocity profile

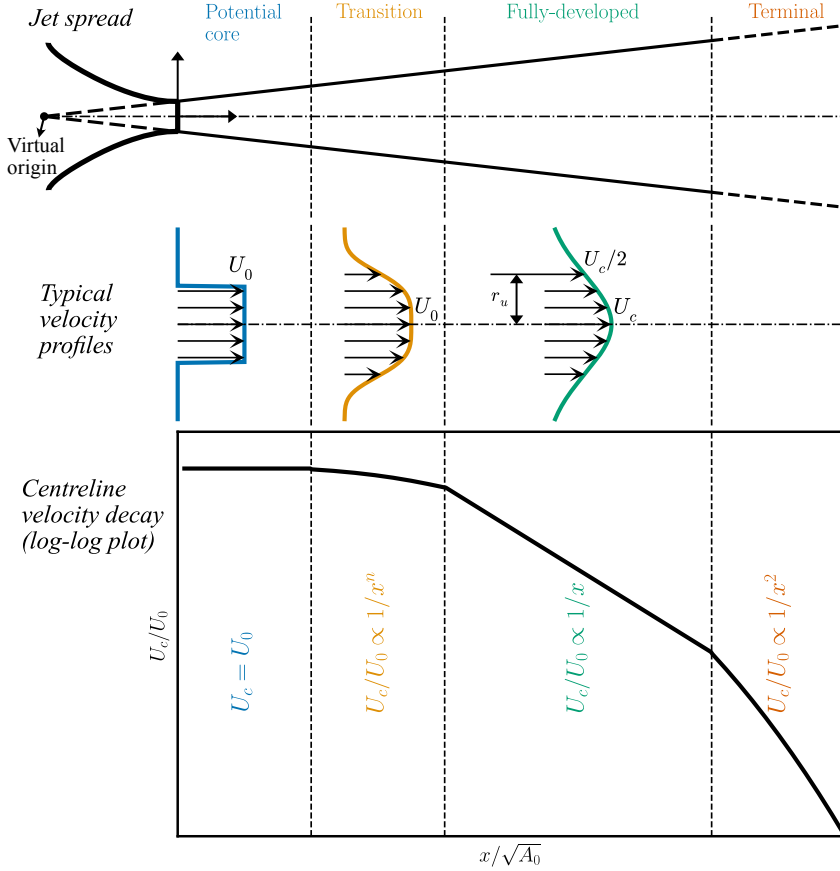


Figure 2.1: Schematic structures of a steady turbulent free jet adapted from [Awbi, 2002]. U_0 is the mean flow velocity; U_c is the velocity at the centreline of the jet; x is the downstream distance from the opening; A_0 is the area of the opening; r_u is the half-width where U_0 is half the corresponding centreline velocity U_c ; n is an index typically between 0.33 and 1.0.

still reflects the inlet condition and typically exhibits a top-hat-shaped profile. In the fully-developed region, the normalised velocity profiles become invariant with axial distance. The flow exhibits self-similar behaviour, and the centreline velocity decays according to a power law whose exponent depends on the jet type and thus on its effective dimensionality. In this region, the velocity profile attains approximately a Gaussian shape when scaled, independent of the inlet conditions. While the mean velocity profile and the spreading rate are indepen-

2 Background

dent of the Reynolds number [Pope, 2000], the exact x/d limits of these regions are not universal but depend on jet type and initial conditions [Hussein et al., 1994]. For instance, for high-Reynolds-number turbulent jets, typical ranges are $[0, 6]$ for the potential core, $[6, 30]$ for the transition region and greater than 30 for the fully developed region. However, these ranges are primarily derived from studies of high-Reynolds-number flows and can vary for lower-Reynolds-number jets [Or et al., 2011], such as breathing jets or jets from ventilation inlets. Additionally, the type of jet influences the ranges of the different regions. Round jets entrain ambient fluid from all directions, leading to stronger mixing, a shorter potential core, and faster centreline decay, whereas plane jets entrain primarily from two sides, which tends to extend the potential core and produce slower decay and spreading [Pope, 2000; Rajaratnam, 1976].

While the classical theory of free turbulent jets provides a useful framework for describing jet development and self-similar behaviour, breathing and ventilation jets and their impact on the surrounding airflow can differ from the theory. These jets are typically characterised by lower Reynolds numbers (Re as low as 10^3), affected by buoyancy effects due to temperature differences, and the strong interactions with surrounding solid boundaries. These complexities make it difficult to integrate indoor airflow assessment into iterative design processes. In this chapter, we introduce common low-cost approaches for studying and modelling these jets and their resulting indoor airflow. Researchers have used experimental measurements and numerical simulations to investigate the behaviour of breathing and ventilation jets and quantify their influence on indoor airflow patterns. Such studies aim to characterise jet spread and entrainment, as well as consequent air distribution, thermal comfort, and airborne contaminant transport in indoor spaces.

2.2 Indoor turbulent free jets - in practice

Experimental and numerical studies of indoor free turbulent jets encompass two aspects: the influence of inlet boundary conditions and the role of ambient conditions on flow dynamics in both the developing and fully developed regions. Inlet boundary conditions are typically characterised by the exit mean velocity profile, turbulence intensity, flow viscosity, and the size of the openings, such as the mouth or nose for exhalation or diffusers for ventilation. These parameters determine the Reynolds number, which governs the flow regime. For typical indoor cases, Reynolds numbers are of the order of 10^3 - 10^4 for exhalation and 10^4 - 10^5 for ventilation diffusers, indicating predominantly turbulent jet behaviour. The behaviour of these free turbulent jets is also strongly affected by ambient factors, such as the presence or absence of nearby solid boundaries, as well as environmental properties including temperature, relative humidity, and the turbulence intensity of the surrounding airflow.

2.2.1 Experimental measurements

Experimental measurement techniques used for indoor airflow measurements can be grouped into two categories: point-wise and global-wise measurements. Global-wise measurement include Particle Image Velocimetry (PIV) [Faleiros et al., 2022; Han et al., 2021; Li et al., 2021], Particle Tracking Velocimetry (PTV) [Ho et al., 2021; Kim et al., 2020] and Schlieren images [Shao et al., 2021; Tang et al., 2009]; however, they are expensive and require special setups that would make it impossible to measure while buildings are occupied and operating normally, deviating from the purpose of the current thesis. Consequently, we only cover point-wise measurements in full-scale indoor environments, which can be continuously carried out for design and for monitoring in occupied buildings.

Point-wise measurements and indoor airflow

Point-wise measurements involve collecting data at specific locations within a space, along the centreline of the breathing jet, to evaluate airflow characteristics and contaminant levels [Sun and Zhang, 2007]. Olmedo et al. [2010] conducted a series of point-wise experimental measurements to characterise the human exhalation flow under different indoor ventilation conditions. The study was carried out in a full-scale test room using a breathing thermal manikin, where both the velocity of the exhaled airflow and the concentration of a tracer gas were measured along the axis of the buoyant breathing jet for different ventilation strategies, including mixing and displacement ventilation. These measurements revealed that the velocity of the exhaled flow decays with distance from the manikin, and that both the peak velocity and the maximum mean tracer concentration decrease as the jet travels downstream, consistent with the decay behaviour expected for free turbulent jets. Moreover, the results demonstrated that the ventilation regime influences the jet's spatial development, with displacement ventilation tending to allow the exhalation flow to penetrate further before decaying compared to mixing ventilation or no ventilation.

Similarly, Licina et al. [2015] conducted point-wise temperature measurements around a breathing thermal manikin in a test chamber to characterise the temperature boundary layer (TBL) and the impact of human respiration on the micro-environment. The study examined mean air temperature and the standard deviation of temperature fluctuations in the region immediately around the manikin's body and breathing zone as functions of room air temperature, body posture and exhalation flow. Along the centreline extending from the mouth, exhalation through the mouth produced a drop in air temperature with increasing distance from the mouth, reflecting the mixing of cooler ambient air with the warmer exhaled air. This behaviour is consistent with the decay of scalar

2 Background

fields in turbulent free jets, where temperature diminishes farther downstream due to entrainment and mixing.

Olmedo Cortés [2012] conducted air velocity measurements under a ceiling-mounted mixing diffuser to characterise the velocity profiles of the jet from the diffusers. The point-wise measurements were not along the diffuser centreline, but were arranged concentrically around its centreline. While the decay of the jet follows the expected log-law velocity decay of a free turbulent jet, the airflow exhibited a quasi-symmetrical pattern mainly due to the rectangular geometry of the room. In contrast to mixing ventilation, Nielsen [2000] showed that in displacement ventilation systems, the supply air is introduced at lower levels in the room. The jet thus spreads along the floor before rising due to thermal buoyancy. In Nielsen [2000], wall-mounted diffusers generate a characteristic floor-level flow pattern where velocity decays with distance from the diffuser's face, but the spread of the jet is strongly influenced by the flow rate, temperature difference, and diffuser shape. The displacement system produces a more constrained, buoyancy-driven profile whose decay and spread depend on thermal stratification and room geometry. These measured profiles illustrate how practical ventilation jets in occupied spaces often deviate from classical free-jet decay laws, reflecting the combined effects of buoyancy, solid boundary interactions, and stratification on the velocity distribution within the occupied space.

Key take-aways:

1. The room's geometry and its obstacles can affect airflow patterns.
2. Buoyancy effects are important for indoor flow characterisation.

Point-wise measurements techniques

Several point-wise measurement techniques exist and can be used depending on what needs to be measured. They are used to measure environmental conditions, different ventilation regimes, and respiratory flows from manikins or people.

Airflow velocity measurements provide insight into airflow speed and direction at specific points. Instruments such as hot-wire [Berlanga et al., 2017; Li et al., 2016], hot-sphere [Berlanga et al., 2017; Bluyssen et al., 2021; Cao et al., 2015; Gao et al., 2017; Liu et al., 2012; Nielsen et al., 2012; Olmedo et al., 2012, 2013], ultrasonic [Dyer et al., 2021; Li et al., 2016; Liu et al., 2012; Zhang et al., 2007a], and vane anemometers [Romano et al., 2015] are typically employed to measure airflow velocity (vectors or magnitude). The measurements from these instruments characterise airflow patterns within indoor environments, including the influence of supply and exhaust locations [Cao et al., 2015; Li et al., 2016; Liu et al., 2012; Olmedo et al., 2013], rotating fans [Gao et al., 2017; Raftery et al., 2019], thermal plumes from occupants or thermal manikins [Li et al.,

2016], recirculation zones [Li et al., 2016; Liu et al., 2012], draught risk [Bluyssen et al., 2021] and breathing jet profile [Olmedo et al., 2013]. These measurements can also provide initial boundary conditions at inlets for CFD simulations [Li et al., 2016; Liu et al., 2012], validate the results of these CFD simulations and quantify the accuracy of modelling ventilation and airborne particle transport [Li et al., 2016; Liu et al., 2012]. These measurements help identify regions where exhaled contaminants are more likely to accumulate due to stagnation and where intervention is needed. Moreover, they can be used to test the impact on the airflow of different furniture configurations [Gao et al., 2017], fan dimensions [Raftery et al., 2019], and the risk of infection between two manikins [Olmedo et al., 2013].

Temperature and relative humidity are environmental indicators that significantly affect aerosol behaviour, influencing their evaporation, dispersion, and deposition. These indicators are measured using environmental data loggers equipped with either a thermocouple [Berlanga et al., 2017; Gilani et al., 2016; Halvoňová and Melikov, 2010; Li et al., 2016; Nielsen et al., 2012; Olmedo et al., 2012, 2013, 2022] or a thermistor [Bolashikov et al., 2015; Licina et al., 2015; Melikov et al., 2002] for temperature and a hygrometer for relative humidity [Ascione et al., 2021]. The measured airflow temperature quantifies thermal stratification and convective flows, such as flows generated by heat sources like occupants. Moreover, relative humidity affects aerosol lifetime and the viability of viruses within aerosols, making monitoring relative humidity important for understanding indoor airborne transmission. These measurements can also help assess thermal comfort and indoor air quality [Bolashikov et al., 2015; Geng et al., 2022].

CO₂ concentrations are frequently used as a proxy for particles in an exhaled breath and an indicator of human occupancy [Berlanga et al., 2017; Zhang and Bluyssen, 2022]. CO₂ concentration measurements are obtained using non-dispersive infrared (NDIR) sensors and can indicate the degree of ventilation effectiveness in real-time. Elevated CO₂ concentrations in occupied spaces may suggest inadequate ventilation and higher risks of airborne transmission. Studies have investigated how many CO₂ measuring sensors are needed in classrooms [Zhang et al., 2022] and whether CO₂ is a good proxy for exhaled particles [Zhang and Bluyssen, 2022]. Furthermore, the decay of CO₂ concentration after occupants' departure is often used to estimate air exchange rates to assess overall ventilation performance [Blocken et al., 2021]. Lastly, CO₂ can also be used as tracer gas to visualise airflow in the room [Gao et al., 2017; Melikov et al., 2002; Wu et al., 2016].

Tracer gas measurements involve the controlled release of an inert gas, such as sulfur hexafluoride (SF₆) [Halvoňová and Melikov, 2010; Li et al., 2016, 2014; Melikov et al., 2002; Wu et al., 2016; Zhang et al., 2007a] or nitrous oxide (N₂O) [Cao et al., 2015; Melikov et al., 2002; Nielsen et al., 2012; Olmedo et al., 2012,

2 Background

2013; Villafruela et al., 2016], at a source point, followed by measurement of its concentration at various locations over time. The inert gas behaviour is similar to that of aerosols emitted from a breathing jet. Gas analysers or samplers are typically used to measure tracer gas concentrations. Tracer gas experiments are particularly used to assess contaminant distribution in the space and its removal efficiency in aeroplane cabins [Li et al., 2016, 2014], and visualise the dynamics in the microenvironment of breathing manikins [Cao et al., 2015; Melikov et al., 2002; Nielsen, 2009].

Particle counters, including optical particle counters (OPCs) [Li et al., 2014; Olmedo et al., 2022; Romano et al., 2015; Zhang and Bluyssen, 2022] and aerodynamic particle sizers (APSS) [Blocken et al., 2021; Liu et al., 2021b; Olmedo et al., 2022], are used to measure airborne particle concentrations and size distributions at specific points. The instruments quantify particle sizes, providing data on particle transport and the effectiveness of air-cleaning devices such as HEPA filters and portable air cleaners.

2.2.2 Computational Fluid Dynamics

Although experimental studies provide valuable insight into indoor airflow and serve as validation data, they also have inherent limitations. Measurements are typically limited to discrete locations or planes, are subject to measurement uncertainty, and offer limited flexibility for systemically investigating different geometries, ventilation strategies, or boundary conditions. Numerical modelling can overcome many of these limitations by providing complete flow-field information and enabling controlled parametric studies. Numerical modelling of indoor jets helps understanding dispersion of respiratory aerosols for infection control [Sheikhnejad et al., 2022; Vita et al., 2023], optimising ventilation design for indoor air quality [Hu et al., 2025; Jiao et al., 2019], and predicting temperature and contaminant distribution [Ascione et al., 2021; Mazumdar et al., 2010]. Computational fluid dynamics (CFD) simulations are the primary tool for these applications, providing field visualisation of velocity, temperature, and scalar transport at a lower cost than experimental visualisation methods such as PIV. The governing equations are the Navier-Stokes equations for mass, momentum, and energy, often coupled with scalar transport equations for aerosol concentration or humidity. To validate CFD results, researchers commonly use experimental data, as discussed earlier in this Section, as ground truth to benchmark the simulation results and assess their accuracy.

Turbulence modelling

CFD simulations can model low-Re free turbulent jets indoors, but they require an appropriate turbulence model. Turbulence modelling approaches include Di-

rect Numerical Simulations (DNS) [Martin et al., 2024; Yerragolam et al., 2024], Large Eddy Simulation (LES) [Vuorinen et al., 2020], and Reynolds-Averaged Navier-Stokes (RANS) or hybrid RANS-LES models [Foster and Kinzel, 2021].

DNS resolves all scales of turbulence by solving the Navier-Stokes equation without approximations. Since the smallest eddy size in a room ranges between 0.01 m and 0.001 m, DNS simulations require a very fine grid to capture the smallest eddies in the turbulent flow in a room. Yerragolam et al. [2024] and Martin et al. [2024] used a grid size of approximately 0.5 and 1.2 billion cells, respectively, to run DNS simulations in relatively small rooms. Additionally, DNS simulations require very small time steps, even for steady-state problems, making them extremely time-consuming. While DNS simulations provide the highest accuracy, they incur an immense computational cost, making them inapplicable to complex turbulent flows [Moin and Mahesh, 1998].

LES uses the filtered Navier-Stokes equations, resolving the large energy-containing eddies on the grid and modelling only the subgrid-scale turbulence. This approach stems from the idea that turbulent flow can be separated into large and small eddies, with the smaller eddies having minimal influence on the evolution of the larger eddies [Deardorff, 1970]. Since the large eddies dominate momentum and heat transport in turbulent flows, accurately simulating them captures the essential flow dynamics. The smaller, subgrid-scale motions are modelled independently of the flow geometry, reducing the need for extremely large computational grids and small time steps like with DNS simulations. Several studies have shown that LES can reliably predict indoor airflow simulations, including forced and natural convection within rooms, respiratory flows and particle dispersion [Berrouk et al., 2010; Saarinen et al., 2015; Vuorinen et al., 2020]. However, its main limitation is its high computational cost, which makes LES impractical for iterative building design. Even with simplifications such as hybrid methods or wall models, simulating indoor airflow, especially when including temperature, can take several days even on high-performance computing systems.

Due to the complexity of accurately modelling turbulent flows and the fact that designers and engineers are primarily concerned with mean and long-term flow values, the RANS equations combined with turbulence models are more commonly used than DNS and LES [Zhai, 2003]. RANS simulations consider all flow fields as statistically averaged values, capturing only the overall characteristics of turbulent motion. The influence of turbulence fluctuations on the mean flow is accounted for using various turbulence models. These models are simplified mathematical representations of turbulent flow behaviour, designed to handle the complex flows encountered in practical applications. Different turbulence models have been developed and used in indoor airflow simulations. The two-equation eddy-viscosity models are the most widely used and can be divided into the $k - \epsilon$ and the $k - \omega$ models. Several studies have compared the performance of these turbulence models for indoor flow applications such as Standard $k - \epsilon$

2 Background

[Ascione et al., 2021; Gilani et al., 2016; Rohdin and Moshfegh, 2007], Realizable $k - \epsilon$ [Gilani et al., 2016; Rohdin and Moshfegh, 2007], Renormalization Group (RNG) $k - \epsilon$ [Gilani et al., 2016; Mazumdar et al., 2010; Rohdin and Moshfegh, 2007; Villafruela et al., 2016; Zhang et al., 2007a], Standard $k - \omega$ [Brohus et al., 2006; Gilani et al., 2016], Shear-stress transport (SST) $k - \omega$ [Faleiros et al., 2022; Gilani et al., 2016]. Two turbulence models have been reported to show higher accuracy for indoor flows RNG $k - \epsilon$ [Chen, 2009; Rohdin and Moshfegh, 2007] and $k - \omega$ SST [Gilani et al., 2016]. The RNG $k - \epsilon$ model improves the prediction of flow separation, streamline curvature, and recirculation, while the $k - \omega$ SST model combines the near-wall accuracy of the $k - \omega$ formulation with the robustness of the $k - \epsilon$ model in the free stream, making it well-suited for simulation combining ventilation and breathing jets.

Temperature modelling

Temperature modelling is important when modelling breathing and ventilation jets because thermal gradients strongly influence indoor airflow patterns and contaminant transport. Since buoyancy forces induced by temperature differences can be of the same order of magnitude as the inertial forces in indoor airflows, their effect on the flow field is non-negligible. Thermal stratification and buoyancy-driven flow arise from temperature differences between supply air and ambient room air, which alter jet development and consequently the dispersion of airborne aerosols indoors [Liu et al., 2021a]. CFD studies of ventilation solve the energy equation to capture these thermal effects, since neglecting temperature gradients can lead to inaccurate predictions of flow patterns [Qian et al., 2022].

Thermal indoor airflow can be modelled using either compressible [Craven and Settles, 2006; Salati et al., 2022] or incompressible [Biswas et al., 2022; Muthusamy et al., 2021] flow, depending on the expected density variations due to temperature differences. When density changes are small, buoyancy effects can be incorporated without fully resolving compressibility. Accurate temperature modelling requires suitable assumptions and boundary conditions at openings and walls to model jets appropriately [Chen and Górlé, 2022; Sun and Wang, 2010]. Good thermal modelling improves predictions of comfort, ventilation effectiveness, and airborne contaminant transport, particularly when studying exhaled thermal jets interact within a cooler ambient air [Liu et al., 2019] or displacement ventilation that relies on temperature differences to effectively exhaust air from an indoor space [Gilani et al., 2016; Zhang et al., 2009].

Particle modelling

Modelling indoor air and exhaled respiratory flows requires choosing how to represent the fluid and any particles. Eulerian-Eulerian and Eulerian-Lagrangian approaches are typically used to model indoor airflow and respiratory flows with particle transport [Lai and Chen, 2007]. The Eulerian-Lagrangian approach treats the fluid phase as a continuous entity while tracking individual particles as discrete entities, making it well-suited for modelling particle flows with complex trajectories [Dbouk and Drikakis, 2020a,b; Keshavarz et al., 2017; Muthusamy et al., 2021; Romano et al., 2015; Wu and Weng, 2021; Xu et al., 2020]. Even though this approach offers detailed insights into particle behaviour, it is computationally expensive to use when testing different design solutions and is therefore out of scope for this thesis. On the other hand, in the Eulerian-Eulerian approach, the airflow and the particles, such as droplets or aerosols, are treated as continuous entities with separate sets of governing equations for each phase. This approach is computationally efficient, especially for design optimisation purposes.

2.3 Conclusion

This chapter introduced the key concepts and background necessary for the remainder of this thesis. The main takeaways are as follows:

1. The room's geometry and its obstacles can affect airflow patterns.
2. Buoyancy effects are important for indoor flow characterisation.
3. Predictions of respiratory jets and indoor airflow depend on modelling assumptions, including the turbulence model, treatment of thermal effects, particle modelling approach, and the required numerical accuracy.
4. There is no clear consensus in the literature on how to model respiratory jets and indoor airflow, as studies adopt different turbulence models, thermal assumptions, and particle representations, leading to variations in modelled results.

3 Milou: a low-cost open-source line-following robot to study indoor air

In Chapter 2, we presented several methods for studying indoor ventilation. Most experimental assessment methods reviewed in Chapter 2 require human operators to set up measurement devices throughout a room. Manually measuring is less reliable due to disruptions in the surrounding air and is more expensive to conduct, especially in the context of PBBD. Nowadays, robots can facilitate low-cost IAQ measurements, provide reliable data, and simultaneously minimise human effort and interference. This chapter, therefore, presents a proof-of-concept for *Milou*, a line-following robot designed to automate IAQ measurements with minimal disruption to the surrounding air. Milou carries a frame with three omnidirectional anemometers to measure airflow velocity magnitude and temperature at predefined locations within a controlled test chamber. To ensure Milou’s data collection reliability, we first evaluate Milou’s repositioning accuracy, its negligible temperature interference by comparing airflow temperature measurements with baseline temperature trends, and its repeatability capabilities for airflow velocity magnitudes. Afterwards, we present two test cases that show Milou’s scalability and usability in indoor environments. Milou’s design and software are open source, enabling further development of mobile IAQ monitoring applications.

3.1 Introduction

As awareness of indoor air quality (IAQ) and its impact on occupant health, comfort, and well-being continues to grow, the need for more efficient methods of IAQ data collection has become increasingly important [Bluyssen, 2009; Jin et al., 2018; Niza et al., 2024; Nunes and Curado, 2023; Yang et al., 2021]. IAQ data, such as airflow velocity, temperature, relative humidity, carbon dioxide (CO_2) levels, and particulate matter (PM), must be closely evaluated to ensure minimal health risks and compliance with ventilation standards [ANSI/ASHRAE, 2022; WHO, 2000]. Traditionally, methods for collecting IAQ data have often been manual, time-consuming, resource-intensive, and prone to inconsistencies, limiting their effectiveness [Geng et al., 2022; Jin et al., 2018; Qian et al., 2016; Yang et al., 2021]. To address these challenges, automating IAQ data collection has become essential, enabling continuous, precise, and efficient data acquisition to support better decision-making and environmental control [Alinezhad et al., 2024].

With advancements in robotics in the built environment [Bier and Mostafavi, 2016; Bo et al., 2022; Promkaew et al., 2024], an increasing number of researchers have been working to automate the collection of various IAQ data. Different mobile robotic systems have been deployed to measure carbon dioxide [Jin et al., 2018; Yang et al., 2021], volatile organic compounds (VOCs) [Jin et al., 2018; Qian et al., 2016], PM_{2.5} [Hu et al., 2020b], temperature [Dyer et al., 2021; Geng et al., 2022], relative humidity [Dyer et al., 2021], and airflow velocity [Dyer et al., 2021; Li et al., 2016]. Depending on the study’s objectives, robots can collect measurements in two distinct ways: at predefined points of interest or continuously as they navigate the indoor environment. In the first approach, robots take measurements at specific points of interest, such as key positions within a room or strategic monitoring spots. For example, Li et al. [2016] used a robot arm on a linear rail to measure airflow velocity magnitude at precise locations in a row of an aeroplane cabin to accurately capture the impact of turning on gaspers within the cabin. Dyer et al. [2021] developed an omniwheel robot, ARES, that measures airflow velocity, temperature, and relative humidity. ARES moves between sampling points in a preprogrammed floor plan, including obstacles, using dead reckoning and an adaptation of the D*-lite algorithm [Likhachev and Koenig, 2002].

Alternatively, in continuous measurement mode, robots gather data as they move, enabling dynamic, real-time collection of environmental data. In fact, Geng et al. [2022]; Jin et al. [2018]; Qian et al. [2016]; Yang et al. [2021] developed spatiotemporal interpolation algorithms to process data from continuously moving robots. They used the sparse measured data to generate high-resolution spatio-temporal maps of complex indoor environments, which help identify localised variations and potential hazards. Qian et al. [2016] employed Gaussian

processes and the Monte Carlo sampling method to create VOC distribution maps using service robots. They showcased the role of probabilistic methods in predicting concentration levels at locations the robots could not reach. Jin et al. [2018] proposed an automated mobile sensing approach to generate high-granularity IAQ data from sparse measurements, demonstrating the advantages of agile sensing strategies over static sensor networks. Likewise, Yang et al. [2021] demonstrated that data collected by a moving robot equipped with a single sensor can better localise a pollutant source than data from 9 stationary sensors. Geng et al. [2022] developed a moving robot to determine its optimal speed for collecting high-resolution temperature measurements to support interpolation algorithms. They discovered that a robot speed of 0.25 to 0.45 m/s is better than 0.60 to 0.80 m/s or 0.10 to 0.20 m/s in collecting reliable temperature data. Hu et al. [2020a] developed Airscope, a cooperative robotic system that utilises distributed deep reinforcement learning to optimise the routing of small robots to achieve better coverage in a complex space.

The above researchers presented pioneering work in the field of IAQ mobile sensing; however, the available literature focuses mainly on optimising the robot’s performance rather than understanding how it impacts its environment. This is particularly relevant as most of these robots carry onboard heat sources that can interfere with the measurements. For instance, Geng et al. [2022]; Jin et al. [2018]; Qian et al. [2016]; Yang et al. [2021] use simultaneous localisation and mapping (SLAM) to navigate indoors. In fact, the robots carry a laptop or an equivalently powerful computing device at the lowest level of the robot to run the SLAM algorithm and perform other data-collection tasks. These devices can easily dissipate up to 150 W of heat¹, which creates buoyancy effects, especially when placed at low levels in the room, and thus interferes with both airflow temperature and velocity measurements. Additionally, the navigation approaches these robots adopt, such as SLAM or dead reckoning, limit the repositioning accuracy over predefined sampling points. To address these gaps, we propose a low-cost open-source robot and focus on testing its repositioning accuracy while reducing its intrusiveness. Then, we deploy it in a test chamber to quantify its impact on the measured airflow temperature and velocity magnitude.

3.2 Methodology

To quantify the impact of a moving robot by measuring airflow velocity and temperature, we first designed and built an autonomous line-following robot, Milou (See Section 3.2.1). Second, we conducted a series of automated measurements in a test chamber of the SenseLab, a laboratory environment at Delft University

¹This is the time-averaged thermal power dissipation of a midrange laptop CPU [Intel, 2024], which is the primary heat source within a laptop.

of Technology [Bluyssen et al., 2018] (See Section 3.2.2), to achieve the following objectives:

1. Investigate the repositioning accuracy of Milou.
2. Investigate the impact of the heat-generating electronic parts of Milou on temperature measurements.
3. Investigate the repeatability of airflow velocity magnitude measurements with Milou.

3.2.1 The line-following robot - Milou

Milou is an autonomous line-following robot designed for IAQ measurements. It navigates a predefined path, stopping at marked sampling points to perform measurements without human intervention. Milou is designed for ease of use and adaptability to different environments and measuring devices. The requirements below guided the design process of Milou:

- Milou should be able to carry a maximum load of 30 kg, the weight of the battery and the measuring equipment;
- Airflow velocity magnitude and temperature measurements with Milou must be reproducible and repeatable;
- Milou should operate fully autonomously, without people in the measurement space, in order not to disturb the air during measurements;
- Milou should not carry significant heat sources, such as laptops, to avoid interference with the measurements.

To achieve the requirements above, Milou integrates motor control, communication, and electrical systems. The motor control system enables Milou to follow a predefined line and stop at predefined points. An array of seven infrared (IR) sensors mounted beneath Plate 1 (see Figure 3.1) detects the line and sampling points, providing real-time feedback to a microcontroller that processes the reflectance values from the IR sensors and adjusts the Servo motors speeds accordingly [Chaudhari et al., 2019]. The motors are rated at 1.3 Nm of torque, ensuring sufficient force to carry the 30 kg load. Milou moves at 0.035 m/s to minimise airflow disturbance. A proportional-integral-derivative control system dynamically regulates those motor speeds, compensating for mechanical inconsistencies and floor irregularities. Additionally, Milou follows the left-hand rule when navigating intersections (Figure 3.2a) and stops at designated sampling points until data collection is complete (Figure 3.2b).

The communication system ensures coordination between Milou's onboard devices and enables a connection with the remote computer. With the latter, we

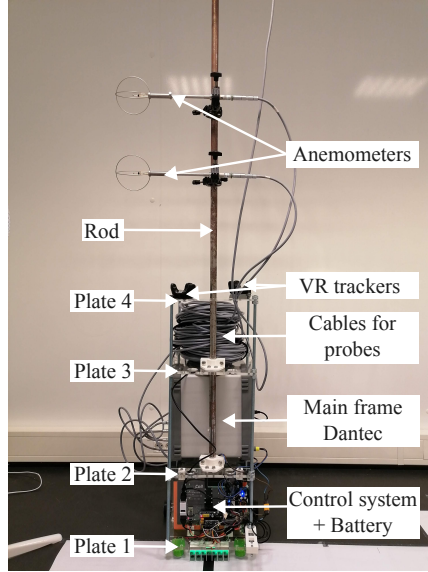


Figure 3.1: Milou in the SenseLab carrying the control, communication, structural, and electrical system, virtual reality (VR) trackers, and the Dantec ComfortSense system.

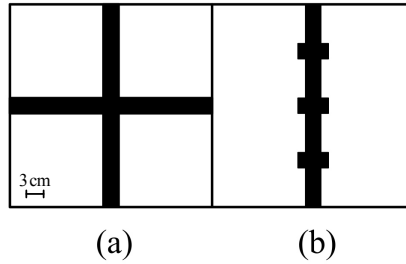


Figure 3.2: (a) represents an intersection where Milou would always take the most left path; (b) represents sampling points where Milou would stop and take measurements.

avoid having powerful on-board computing devices, such as laptops, on Milou. Instead, we use a microcontroller and a Raspberry Pi, with a heat emission rate of 2 to 5 W [Arduino[®], 2023; Raspberry Pi Foundation, 2017], an order of magnitude lower than that of a typical laptop. The microcontroller interprets IR sensor data and transmits control signals to the motors and, when necessary,

the Raspberry Pi. To minimise onboard heat sources, the Raspberry Pi acts as a wireless access point, relaying data between onboard devices and a remote computer outside the measured indoor space. Milou can also be controlled via Bluetooth for remote manual operation. Figure 3.3 shows the block diagram of the communication system on Milou.

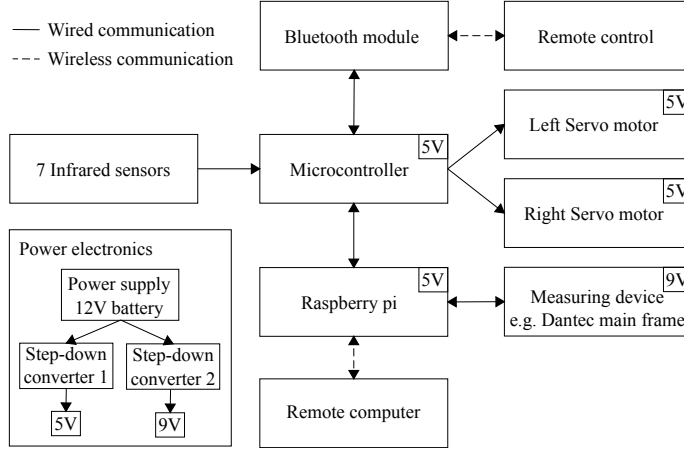


Figure 3.3: Block diagram of the communication system (single arrowhead means one-way communication, double arrowhead means two-way communication).

A 12V LiFePO₄ battery with a capacity of 38Ah powers three main electrical parts: the microcontroller, the Raspberry Pi and the Dantec main frame. Two step-down converters regulate voltage levels: 9V for the Dantec main frame (further explained in Section 3.2.2) and 5V for the other components. The battery provides up to 15 hours of continuous operation, after which Milou experiences difficulty rotating at intersections due to power depletion (See A.1 for more detail on Milou’s electrical components).

Milou’s compact structural design ensures the robot’s stability and enables it to manoeuvre in confined spaces. Milou consists of three 280x260x8mm plexi plates, one 280x260x4mm plexi plate, and a 1.75 m hollow tube for mounting measuring devices. The four plates are vertically mounted to minimise the structure’s footprint. Figure 3.1 shows the rod and the plates that hold the components together. The four plates are functionally allocated as follows:

- Plate 1 houses the control system and the battery, positioned low to maintain a stable centre of gravity.

- Plate 2 supports the mounting rod and, in this study, the Dantec ComfortSense system’s main frame [DantecDynamics, 2022].
- Plate 3 holds the cables of the hot sphere anemometers (HSAs) used for measuring airflow velocity magnitudes and temperature.
- Plate 4 holds two HTC VIVE Virtual Reality (VR) trackers to monitor Milou’s position at measuring points. The two trackers are positioned at two opposite corners of Plate 4, 258 mm apart.

The tube holds three anemometers at heights of 1.1, 1.3, and 1.7 m above the floor level (see Figure 3.1), following the [EN Standard - EN 12599:2012 \[2012\]](#) for measuring heights to assess ventilation. Plates 2, 3, and 4 can be customised to accommodate alternative measuring devices.

3.2.2 Experimental setup

To evaluate Milou’s performance and impact on the airflow, we conducted a series of measurements (see Table 3.1) in one of the test chambers of the SenseLab (3.73 x 2.22 x 2.12 m) at the Delft University of Technology [Bluyssen et al., 2018], in November 2024 and January 2025.

Table 3.1: Experimental setups and settings. T: temperature; U: airflow velocity magnitude; HSA: hot sphere anemometers; VR: virtual reality; HOBOS are temperature loggers.

Setup	Devices	Measured variables	Ventilation	Laps
1 - Measure repositioning accuracy	2 VR trackers	Position of trackers	Chamber airflow rate of 140 m ³ /h	3
2 - Measure impact on temperature measurements	3 HSAs + HOBOS	U + T	Chamber airflow rate of 140 m ³ /h	4
3 - Measure velocity magnitude repeatability	3 HSAs	U	Chamber airflow rate of 140 m ³ /h + 2 fans	4 4

To conduct these measurements, we employ three different measuring devices. First, the Dantec ComfortSense system [DantecDynamics, 2022] comprises the following elements:

- a main frame that connects, synchronises and processes the raw data from different sensors;

3 Milou

- probes, which in our case are three HSAs that measure airflow velocity magnitude and temperature;
- software to run measurements and extract the data, it runs on a remote computer as explained in Section 3.2.1.

Second, we use six HOBO data loggers (HOBOS) [Onset Computer Corporation, 2022], which are compact devices to measure temperature, relative humidity and CO_2 levels. For this study, the purpose of these HOBOS is to monitor temperature in the chamber with and without Milou turned on. For the location of the HOBOS in the chamber, refer to Supplementary Materials in Hobeika et al. [2025b]. Finally, we use two HTC VIVE VR trackers with two lighthouses to position Milou in the chamber. Table 3.2 presents the technical specifications of the measuring devices used in this study.

Table 3.2: The specifications of the measuring devices used. OR: Of Reading.

Measuring device	Measured parameter	Range	Accuracy
VR trackers	X, Y, Z location	0 to 7 m	2.57 ± 1.07 mm at constant bright lighting conditions [Kulozik and Jarrassé, 2024]
Dantec omnidirectional HSA	Airflow velocity magnitude	0.05 to 5 m/s	0-1 m/s: $\pm 2\%$ OR ± 0.02 m/s; 1-5 m/s: $\pm 5\%$ OR; 5-10 m/s: $> \pm 5\%$ OR
Dantec omnidirectional HSA	Temperature	-20° to $70^\circ C$	$0^\circ C$ to $+45^\circ C$: $\pm 0.2^\circ C$; $-10^\circ C$ to $+60^\circ C$: $\pm 0.3^\circ C$; $-20^\circ C$ to $+70^\circ C$: $\pm 0.5^\circ C$
HOBO [®] MX1102A Data Logger	Temperature	0° to $50^\circ C$	$\pm 0.21^\circ C$ from 0° to $50^\circ C$

For each setup, in one lap along the path, Milou moves from A to J and stops at each of the ten points for five minutes while the measuring devices collect data. One complete lap over the ten points is 3.7 m in length (See Figure 3.4 for the path).

Setup 1: Evaluating the repositioning accuracy of Milou

Milou’s trajectory along the line is continuously adjusted using proportional-integral-derivative control. Due to continuous corrective adjustments along the

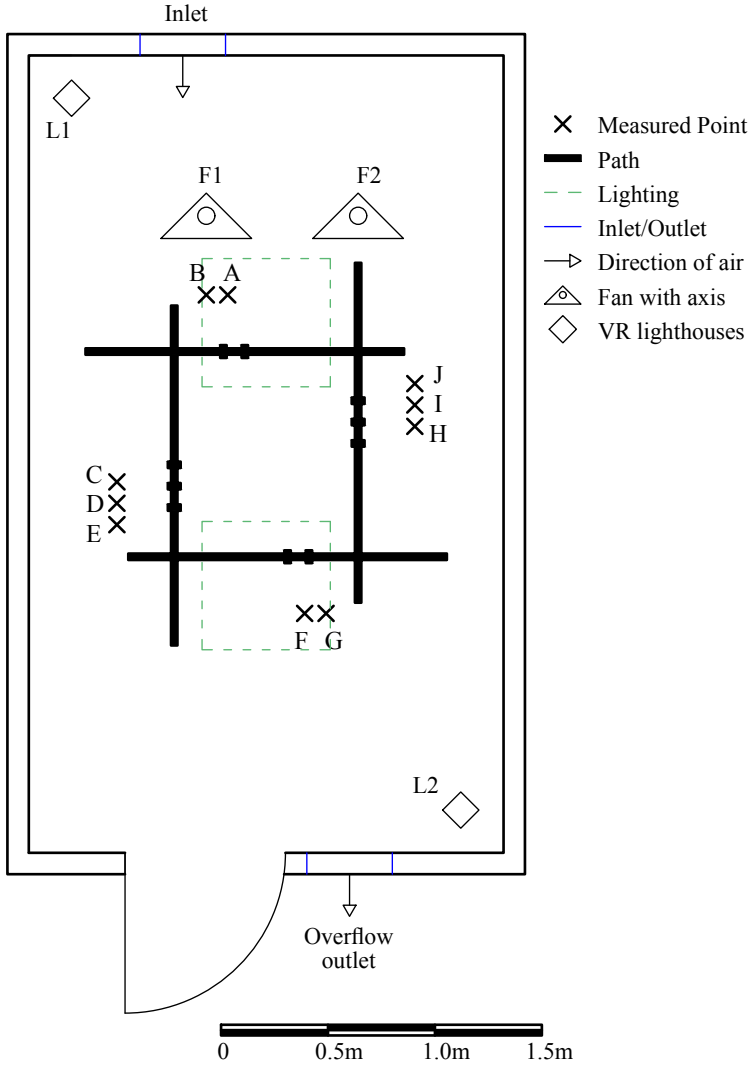


Figure 3.4: Plan view of the test chamber with the location of the path, fans (axis of fan at 1.1 m height), VR lighthouses (at 1.6 m height), the ceiling lights and the inlet (at 0.19 m height) and overflow outlet (at 1.68 m height) of the ventilation system.

3 Milou

line, the robot exhibits lateral oscillation, which may affect its repositioning accuracy. To assess whether Milou can reliably stop at predefined points despite these continuous corrections, we track its movement using two VIVE VR trackers mounted on Milou's Plate 4. The robot loops over the path three times (See Figure 3.4 for the path). The lighthouses of the VR trackers are positioned at opposite corners of the chamber at a height of 1.6 m (See Figure 3.4).

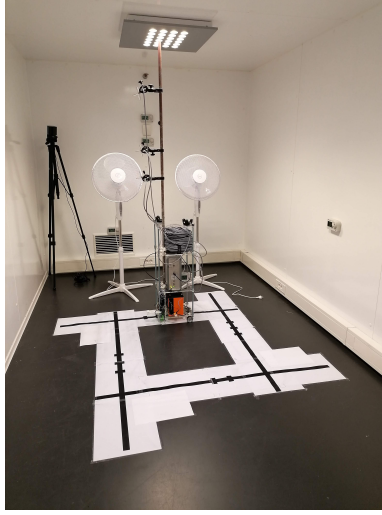


Figure 3.5: Milou on the path inside the test chamber with the two fans and the lighthouses.

Setup 2: Quantifying the impact of Milou on the temperature measurements

Milou's base contains elements that act as heat sources. To assess whether the temperature emitted by Milou's control board interferes with other temperature measurements, we compare measurements with Milou operating in the test chamber against a baseline trend. This baseline was established by measuring the chamber's temperature with only the ceiling lights turned on (Milou was off). Since the ceiling lights alone have been shown to cause a measurable increase in temperature (see Supplementary Materials in Hobeika et al. [2025b]), this setup will help determine if the robot's control board contributes any significant variance or follows the same trend as observed in the baseline scenario.

The test chamber for Setup 2 has ceiling lights and ventilation on, with an inlet airflow temperature of 21°C and an airflow rate of $140\text{ m}^3/\text{h}$. The ventilation

system in the room consists of a supply grill at the back of the chamber, at a height of 0.19 m, and an outlet grill, opposite the inlet grill, at a height of 1.68 m, based on overflow. The chosen ventilation rate allows a background flow exceeding 0.05 m/s (the HSAs' threshold). Five HOBOS are distributed across the four walls of the room (see Supplementary Materials in [Hobeika et al. \[2025b\]](#)), while one HOBOS is mounted on Milou's Plate 2. Milou loops over the path four times while the HSAs measure airflow velocity magnitude and temperature. We then check whether the static measurements from the HOBOS and the dynamic measurements from the HSAs match the baseline trend.

Setup 3: Evaluating the repeatability of airflow velocity magnitudes with Milou

Finally, we investigate the repeatability of magnitude measurements across four laps in two magnitude ranges: low (0 to 0.3 m/s) and high (1 to 5 m/s). We want to check whether buoyancy from Milou's base would interfere with the magnitude of airflow velocity measurements over time. For the low ranges test, we use the magnitude measurements from Setup 2, and for the high ranges test, we run an additional setup with two fans on in the chamber (See Figures 3.4 and 3.5). The two fans ensure that, at chosen points of interest, the magnitude range remains above 1 m/s. Fan 1 is placed to directly measure the momentum in the centreline of the fan's jet at point B (the outer cage of the fan is 0.1 m away from point B), and Fan 2 is placed to measure outside the centreline of the fan's jet at points H, I and J. The fans are tilted 10° upwards, with the fan axis at a height of 1.1 m from the floor. Milou repeats the loop four times, collecting measurements of airflow velocity magnitude.

Statistical analysis

When analysing the VR positioning measurements, we compute the mean positional error of both trackers, the standard deviation of the positional error of both trackers, the 95% confidence interval of both trackers, the angular error of the entire setup, the standard deviation of the angular error of the setup for all three rounds, and the 95% confidence interval of the angular error. When comparing IAQ datasets, we use a mean normalisation to remove the noise from the measured data given by:

$$x^* = \frac{x - \mu}{\max(x) - \min(x)} \quad (3.1)$$

We also employ a polynomial regression model to analyse and compare the trends in temperature measurements across the datasets. Specifically, we use a second-degree polynomial regression (parabolic) based on Adjusted R^2 comparisons.

Table 3.3 shows that, for our datasets, a second-degree polynomial already shows perfect fit with the HOBOS temperature measurements. For the statistical sig-

Degree polynomial	Adjusted R ² HOBOS with Milou	Adjusted R ² HOBOS no Milou
1	0.95	0.98
2	1.00	1.00
3	1.00	1.00
4	1.00	1.00

Table 3.3: Adjusted R² values when fitting HOBOS temperature datasets to a first-, second-, third-, and fourth-degree polynomials.

nificance tests, since our data are not normally distributed and the datasets compared are dependent, we use the Wilcoxon signed-rank test [Wilcoxon et al., 1970] for paired comparisons and the Friedman test [Friedman, 1937] for comparing four datasets. We check whether the p-value is less than 0.05 for a 95% confidence interval.

3.3 Results and discussion

3.3.1 Repositioning accuracy

Based on Table 3.4, tracker 1 and tracker 2 had mean repositioning error of 2.1 ± 1 mm and 4 ± 5 mm, respectively, across all ten points over the three laps, with maximum observed mean error of 4 mm and 17 mm. However, after visually investigating the measured points and conducting a Grubb’s test with $\alpha = 0.05$, we concluded that points F and G are outliers. The low accuracy at points F and G is a local occurrence that only affects tracker 2, likely due to occlusion or excessive reflectance in that part of the room. Therefore, we recompute the tracker 2’s mean error without points F and G and get a mean repositioning error of 2.1 ± 1 mm, with a maximum observed mean error of 4 mm for both trackers. The maximum observed positional error of both trackers is thus 0.1% of the total distance travelled in one lap (3.6 m). Additionally, Table 3.4 shows the mean angular error of Milou’s base based on the repositioning error of both trackers. Excluding points F and G, the mean angular error of Milou ranged from $0 \pm 0^\circ$ at point A to $0.6 \pm 0.7^\circ$ at point C.

To contextualise the capabilities and limitations of Milou’s line-following navigation, we compare it with three other navigation approaches: dead-reckoning, SLAM-based, and rail-based systems. Dyer et al. [2021] used a dead reckoning navigation algorithm to move their robot, ARES, to predefined points in a room. The main advantage of their approach is avoiding physical path setup; however,

Table 3.4: Repositioning accuracy per VR tracker and angular accuracy for the pair of trackers at each point. L: Total distance travelled in one lap [mm], T1: Tracker 1, T2: Tracker 2, $\overline{\mu_p}$: mean positional error [mm], σ_p : standard deviation of positional error [mm], CI_p : 95% confidence interval of mean positional error [mm], $\overline{\mu_a}$: mean angular error [$^\circ$], σ_a : standard deviation of angular error [$^\circ$], CI_a : 95% confidence interval of mean angular error [$^\circ$].

Point	L	T1 $\overline{\mu_p}$	T2 $\overline{\mu_p}$	T1 σ_p	T2 σ_p	T1 CI_p	T2 CI_p	$\overline{\mu_a}$	σ_a	CI_a
A	235	1	1	0	0	± 0	± 0	0.0	0.0	± 0.0
B	245	1	1	0	1	± 0	± 1	0.3	0.3	± 0.4
C	1005	1	3	0	1	± 0	± 1	0.6	0.7	± 0.8
D	1105	4	2	1	1	± 2	± 1	0.5	0.6	± 0.7
E	1205	4	4	2	2	± 2	± 2	0.3	0.3	± 0.4
F	1965	2	6	0	2	± 0	± 2	1.0	1.1	± 1.3
G	2065	3	17	1	1	± 1	± 12	2.0	2.4	± 2.7
H	2825	2	2	1	1	± 1	± 1	0.1	0.1	± 0.2
I	2925	1	2	0	0	± 0	± 0	0.2	0.2	± 0.2
J	3025	2	2	1	1	± 1	± 1	0.3	0.3	± 0.4

it suffers from accumulated drift over the distance travelled, with 2.9 mm and 2.0 mm drift per meter in the x and y directions, respectively. The drift reduces the accuracy of the measurement locations, especially towards the last six points of the fifteen measured points. The 0.5° angular error was a limitation of ARES, leading to greater position variance towards the end of the path. This accumulated drift limits the use of ARES in larger spaces [Dyer et al. \[2021\]](#), an issue that Milou’s line-following approach avoids. SLAM-based approaches [\[Geng et al., 2022; Jin et al., 2018; Qian et al., 2016; Yang et al., 2021\]](#) also benefit from the lack of a physical path by offering the highest degree of autonomy and environmental adaptability but suffer from a low relative accuracy (± 20 mm [\[Jin et al., 2018\]](#)) and requires significant computational resources and system tuning. [Li et al. \[2016\]](#) used a rail to achieve high navigation precision (0.5 mm) with minimal computation load. The disadvantage of rail-based robots is their limited scalability to more complex paths, due to their reliance on costly, fixed rail systems and inflexible route designs.

On the other hand, Milou’s line-following feature avoids drift while maintaining millimetre-accuracy, outperforming both dead-reckoning and SLAM-based navigation. As shown in Table 3.4 and Figure 3.6, the error does not increase with distance travelled. Points H to J have lower mean errors than points D and E, even though they are measured earlier in the loop. Milou also provides a more flexible route design compared to the rail-based approach (See Table 3.5 for a summary of all navigation approaches). Milou’s navigation system trade-offs make it suitable for most indoor airflow studies.

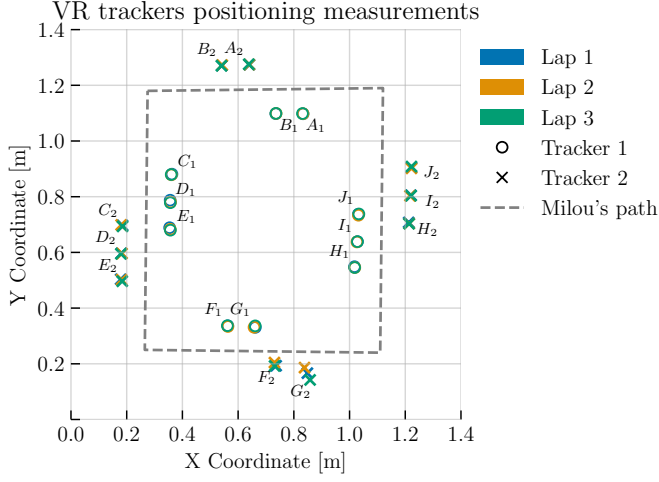


Figure 3.6: Milou’s positions measured by the VR trackers. See Figure 3.4 for path location in the chamber.

Table 3.5: Comparison between Milou and the robots with different navigation approaches from the literature. ‘-’ means the information was not reported in the papers.

Navigation system	Line-following (Milou)	Dead-reckoning [Dyer et al., 2021]	On rails [Li et al., 2016]	SLAM-based [Jin et al., 2018] [Yang et al., 2021] [Qian et al., 2016] [Geng et al., 2022]
Accuracy	2.1 ± 1 mm	2.9 mm/m (x), 2.0 mm/m (y)	0.5 mm	20 mm [Geng et al., 2022]
Cost	1,000 euros	800 USD	-	-
Physical setup effort	Medium - install lines	Low	Very high - install rails	Low
Computational load	Low	Low	Low	High
Main limitations	Manual route changes	Accumulated drift	Inflexible routes	Sensors and map tuning

3.3.2 Temperature distribution measurements

To understand Milou’s impact on the airflow temperature measured in the test chamber, we first evaluate the temperature distribution across the 10 points, then compare the trends measured by the different HOBOS and HSAs. Figure 3.7

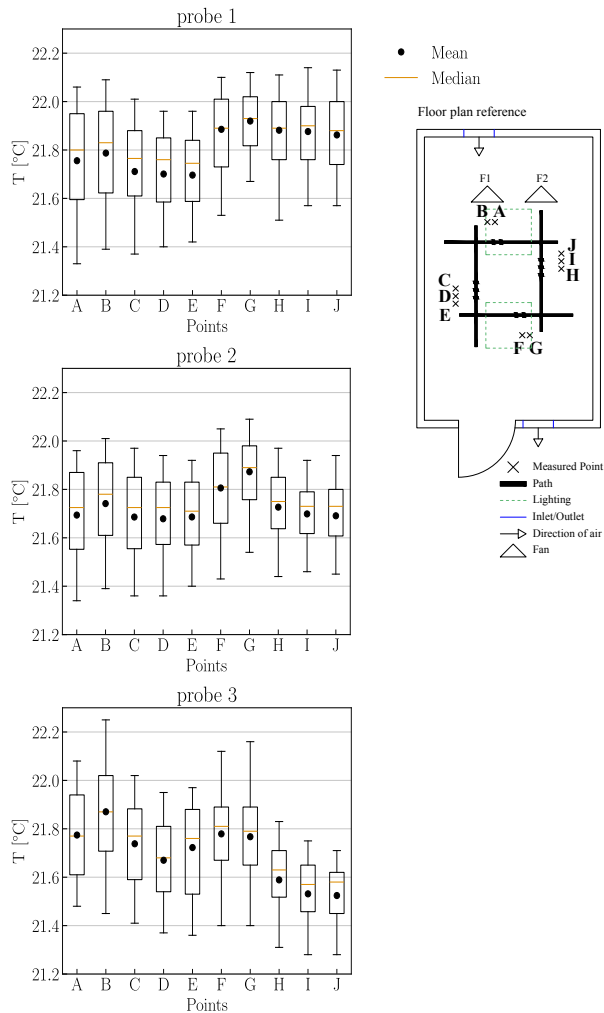


Figure 3.7: Boxplots of the temperature (T) measured over the four laps at each point at probes 1 (at 1.1 m), 2 (at 1.3 m), and 3 (at 1.7 m). Under the legend, a reference floor plan helps locate the ten points in the test chamber.

shows the temperature measured over the four laps at each of the ten points on the path. We first observe that points A to E measure, on average, lower temperatures than points F to J. This temperature difference is due to the cooler airflow travelling from the inlet to the outlet in the chamber, as points A to E are located within the primary airflow path (see A.2). Furthermore, points A and B, and points F and G, measure higher temperatures than the other points along the path. At these points, the probes are closer to the ceiling lights, the heat source we are using to validate Milou’s measurements. Probe 3 clearly shows the difference because it is closest to the ceiling lights, 42 cm below them. Finally, we see that points H to J at probe 3 measure lower temperatures than probes 1 and 2 at the same points and also lower than points C to E. This might seem counterintuitive, as buoyancy would suggest that probe 3 should measure a higher temperature than probes 1 and 2, and those points are not in the main airflow pattern of the ventilation (points H to J should measure higher than points C to E). However, this is due to the airflow patterns from the ventilation, which probe 3 detects in that part of the chamber (see Section 3.3.3 and A.2). The fact that devices on Milou can detect such airflow patterns, in agreement with numerical simulations that do not include Milou, shows that Milou does not interfere with the existing airflow patterns in the chamber.

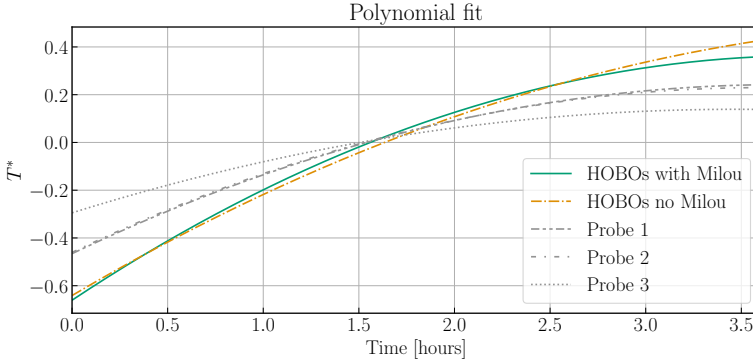


Figure 3.8: Second-degree polynomial fit of normalised temperature (T^*) measured with the HOBOS, with ceiling lights on, with and without Milou on in the test chamber and measured with the HSAs at all three probes.

To better compare trends measured with different devices in the room, we fit the normalised data from the four laps with a second-degree polynomial (see Figure 3.8). The temperature trend measured with the HOBOS over an entire day with and without Milou shows no significant difference (p-value of Wilcoxon test = 0.95). The maximum absolute temperature difference between the two datasets is 0.2 °C, which is within the HOBOS’ measurement accuracy. The

three probes also show three positive trends that are not significantly different from the trend measured without Milou (p-values for the Wilcoxon test = 0.94, 0.92, and 0.94 for probes 1, 2, and 3, respectively). The differences we see visually in Figure 3.8 are due to two factors. First, the HOBOS and the HSAs have two different temperature-measuring mechanisms, where a HOBOS employs a thermistor [Onset Computer Corporation, 2022] and a HSA relies on a thermocouple [Jensen et al., 2007]. Second, the HOBOS and the HSAs are positioned at different heights and locations in the room. The HOBOS on the wall tend to measure air that is less well mixed than the air measured by the HSAs on Milou, which measure in the middle of the room. We also see that probes 1 and 2 show the same temperature trend because they are relatively close to each other, whereas probe 3 shows a smaller slope. This difference shows that temperature buildup differs across locations in the room. Since these results further confirm the low-temperature impact of electronic devices on Milou’s base, this approach could be applied to other robots used to collect indoor temperatures.

3.3.3 Airflow velocity magnitude

To determine whether the buoyancy effect from Milou interferes with airflow velocity magnitude (U) measurements, we investigate U at each of the ten points over the four laps, with fans on (Setup 3) and off (Setup 2). Figure 3.9 shows the airflow velocity magnitude variations over the ten points when fans are off - Setup 2. Probe 1 shows higher U values at points C to E than at the other points. Those three points are located in front of the mechanical ventilation inlet and thus show higher magnitudes. At probe 2, U is higher on points C to E than on points A, B, F and G, in agreement with observations at probe 1 at the same points. However, points H to J show higher U values than other points at probe 2 and than points H to J at probe 1. This shows the beginning of the recirculation region in that part of the room that we observe in A.2. Probe 3 shows low U values at points A to E and higher U values at points F to J. At points H to J, the higher U values account for the temperature drop observed in Section 3.3.2. These results show how the main airflow from the inlet to the outlet can create recirculation regions elsewhere in the room. Figure 3.9 also shows velocity magnitude sampled from a computational fluid dynamics (CFD) simulation where the CFD data falls mostly in the interquartile range of the experimental data and within the accuracy of the HSAs ± 0.02 m/s from the means at all probes. Based on both measurements and simulations, we observe minimal interference from Milou at low velocities in the chamber.

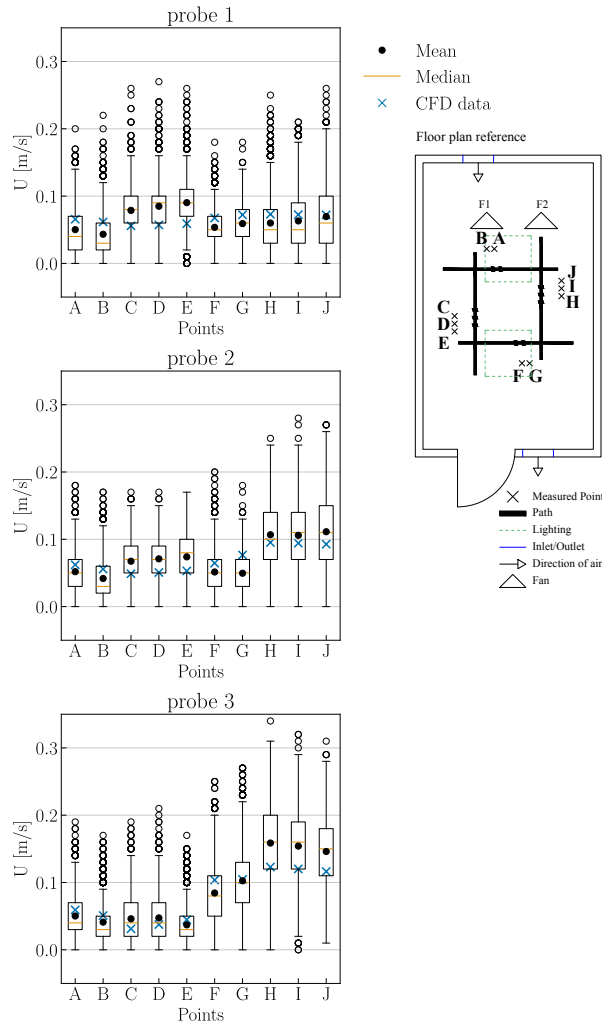


Figure 3.9: Boxplots of the airflow velocity magnitude (U) measured over the four laps at each point, at probes 1 (at 1.1 m), 2 (at 1.3 m), and 3 (at 1.7 m), with fans off - Setup 2. Under the legend, a reference floor plan helps locate the ten points in the test chamber.

Figure 3.10 shows the airflow velocity magnitude variations over the ten points when the two fans are on - Setup 3. Given the proximity of points A and B to

Fan 1 (see the reference plan in Figure 3.10), probes 1 and 2 measure the highest U values compared to all other points, with probe 1 measuring 1 m/s on point A and 2 m/s on point B and probe 2 measuring 2.5 m/s on point A and 3.2 m/s on point B. Conversely, probe 3 on points A and B measures lower U values than probes 1 and 2, due to its higher position than Fan 1. Probe 3 on points A and B thus measures the background flow, measuring around 0.5 m/s. At points C to E, probes 1 and 2 measure around 0.5 m/s, as would be expected, with Fan 1 tilted up, not directly reaching probes 1 and 2 at 1.1 and 1.3 m. Probe 3, on the other hand, measures relatively higher magnitudes around 1.2 m/s. Further away from the fans, at points F and G, all probes measure, on average, lower than all the other points. Similarly to points C to E, due to the upward tilt of the fan, there is a small difference between the probes at points F and G, with the difference increasing in magnitude as the probes are higher. Since Fan 2 is not tilted upwards, on points H to J, probe 2 measures around 2 m/s, a higher U value than probe 1 (1 m/s) and probe 3 (1 m/s). Based on these observations, the probes on Milou appear to measure U variations as expected from the fans' tilt and their proximity to the sampling points.

To assess the repeatability of U over the four laps, we normalise each lap's data in both setups to remove noise for the comparison study. Figure 3.11 shows the boxplots of U at point A during Setup 2 and 3. At each probe, the median and the mean of U at each lap fall within the box of all the other laps. The interquartile ranges, the spread of the whiskers, and the occurrence of outliers of the four laps are similar at each probe. Additionally, the p -values from the Friedman test are all greater than 0.05, and the 95% confidence intervals overlap, indicating no statistically significant difference between the four laps. Only probe 1 at point A yields a p -value of 0.02. Inspection of the individual lap measurements indicates that this result was primarily influenced by the skewed measurements from Lap 2 compared to the other three laps. One possible explanation for the skewed measurements at only one lap is the inherent variability of indoor airflow rather than a systematic measurement error. The remaining 9 points across all three probes and probe 2 and 3 at point A show no significant difference between the laps (see Supplementary Materials in Hobeika et al. [2025b]), suggesting that the temperature from Milou's base mixes with the surrounding air before reaching the probes on Milou. Overall, Milou demonstrated repeatable U measurements at 29 of 30 points, indicating reliable data collection.

3.3.4 Scalability test

This Section focuses solely on evaluating Milou's performance and scalability in more complex spaces. Any measurements are beyond the scope of this section and are therefore not presented here. To test Milou's scalability, we conducted a measurement campaign in the Experience Room of the SenseLab (6.1 x 4.2 x 2.7

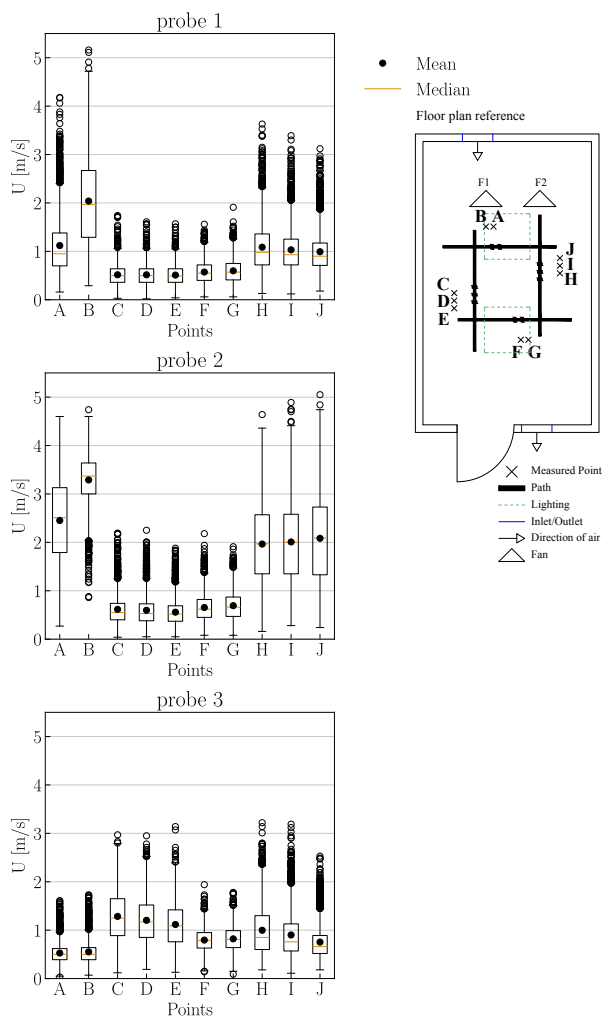


Figure 3.10: Boxplots of the airflow velocity magnitude (U) measured over the four laps at each point, at probes 1 (at 1.1 m), 2 (at 1.3 m), and 3 (at 1.7 m), with fans on - Setup 3. Under the legend, a reference floor plan helps locate the ten points in the test chamber.

m). The ventilation in the Experience Room is set to mixing, where air enters the room from four ceiling grills and exits from two perforated plinths at the bottom

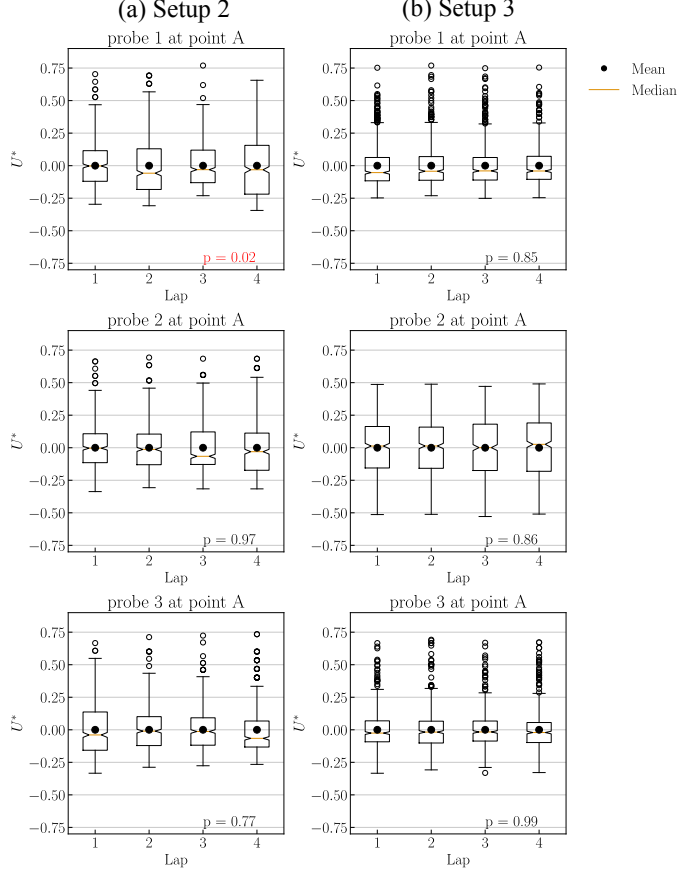


Figure 3.11: Notched boxplots of the airflow velocity magnitude (U) measured at point A at each lap with fans off - Setup 2 (a) - and with two fans on - Setup 3 (b). The notches show the 95% confidence interval around the median. The p-value is the result of the Friedman test across the four laps and should be greater than 0.05 to prove the repeatability of the results.

of the two shorter walls of the room [Bluyssen et al., 2018]. The furniture in

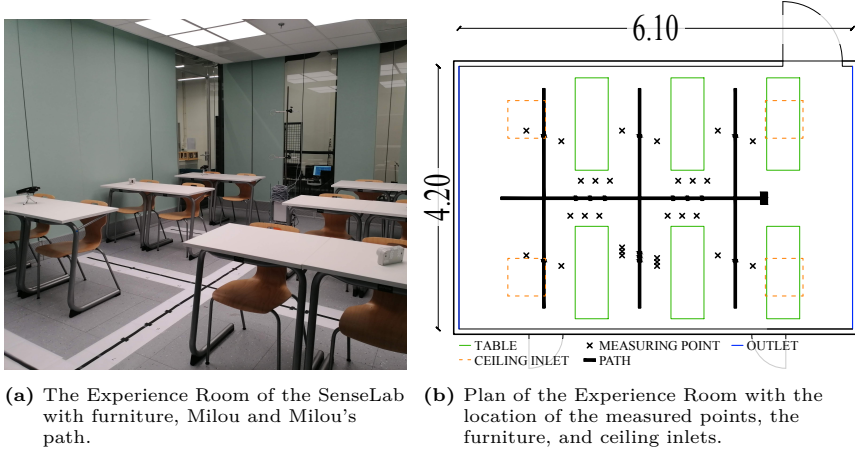


Figure 3.12: Overview of Milou's deployment in the Experience Room in the SenseLab.

the Experience Room replicates a classroom setting with three rows of tables separated by an aisle (See Figure 3.12a). We deployed Milou over a 27.3 m long path with 28 measuring points between the furniture and measured air velocity magnitude at a height of 10 cm from the floor to study the impact of furniture on draught at feet level (See Figure 3.12b). Milou successfully measured all points over three laps of the path, accomplishing the task four times faster than a human operator.

3.4 Limitations and future work

We recognise that our experiments and Milou as a proof-of-concept have a number of limitations:

1. All the measurements in this study were carried out under an airflow temperature range between 21 and 22°C, typical temperatures for classroom or office settings, and one ventilation regime with fans on and off. Therefore, all the results apply to these conditions. Further investigation might be needed under different temperature and ventilation conditions.
2. The HSAs that we use in this study have a relatively high minimum threshold of 0.05 m/s and only measure airflow velocity magnitude. Using more

sensitive devices that can measure the airflow velocity vector could detect smaller variations relevant to assessing Milou's interference with the surrounding airflow.

3. To avoid interference with the airflow measurements, Milou currently stands still for a period of 5 minutes at each sampling point to measure, and it does not measure while it is moving. Future work could investigate whether Milou can reliably measure airflow velocity while moving continuously and, if so, determine the optimal speed. This is similar to what [Geng et al. \[2022\]](#) did for reliable and continuous airflow temperature measurements.
4. To avoid the preparation time for the line path and to extend Milou's application to dynamic and unmapped environments, it is worth investigating alternative methods that require less preparation time and low computational power, such as lightweight SLAM that does not require a powerful computing device. Lightweight SLAM can be combined with floor stickers to mark sampling points, achieving low preparation time and high repositioning accuracy.
5. Milou should be tested in more spaces, such as bigger classrooms or offices, to evaluate and improve its capabilities.

3.5 Conclusion

Milou is a proof of concept for low-cost, low-interference automated IAQ measurements. To investigate the impact of Milou on airflow velocity magnitude, we tested it in a controlled laboratory setup. We first established Milou's repositioning accuracy over a repeated path. Second, using three omnidirectional anemometers on Milou at three different heights and six HOBOS deployed in the room, we found that the electrical devices on Milou's base do not affect temperature measurements in the test chamber. Finally, we investigated the repeatability of airflow velocity magnitudes measured with Milou, which showed repeatable measurements at 97% of the points.

Based on the results, we conclude that Milou does not interfere with the measurements and allows small airflow changes around the chamber to be detected. With its ability to navigate tight, complex spaces while carrying other measuring devices, Milou enables future applications, such as integration into smart building management systems to continuously monitor air quality and provide real-time data for optimising mechanical ventilation systems in offices or classrooms. Automating IAQ measurements thus has the potential to improve the efficiency of collecting indoor data across different building applications.

Data availability

All of Milou's code, blueprints, and schematics have been made publicly available under an open-source licence. This makes it easy for others to reproduce and further improve on its design. The code, the blueprints for Milou, and the post-processing code are publicly available at: <https://doi.org/10.5281/zenodo.15082684>. The raw data for the measurements are publicly available here: <https://doi.org/10.4121/41307b71-2096-4a31-82ba-f523a18c109a>.

4 Exploring the impact of Reynolds-Averaged Navier-Stokes solvers on the indoor modelling of a breathing jet

Ideally, PBBD could benefit from an iterative design process involving both collaboration between designers and specialists and the evaluation of multiple design alternatives. While this cannot be readily achieved through the low-cost automated mobile monitoring of indoor airflow presented in Chapter 3, it can be effectively supported by CFD simulations that enable the evaluation of multiple design alternatives. Numerically studying indoor airflows and ventilation, especially under diverse environmental conditions, requires modelling airflow velocities, temperature distributions, and at least passive scalar concentrations. This chapter showcases the validation and performance of three Eulerian-Eulerian solvers for predicting air- and respiratory-flow patterns, accounting for airflow temperature distributions and passive scalar concentrations. We first present one solver without heat transfer, and two solvers including heat transfer. We then validate the solvers against measurements using the robot from the Chapter 3 and further work in the literature to understand how closely they match the jet decay theory and their computational efficiency. Based on these metrics, the chapter concludes with the most suitable solver for different ventilation design exploration.

This chapter is based on the following conference abstracts:

Hobeika, N., García-Sánchez, C., & Bluysen, P. M. (2023). Validation of different Eulerian and Lagrangian solvers of aerosol dispersion in indoor spaces. Paper presented at 16th ICWE International Conference on Wind Engineering, ICWE2023, Florence, Italy.

Hobeika, N., Bluysen, P. M., & García-Sánchez, C. (2026). Exploring the impact of Reynolds-Averaged Navier-Stokes solvers on the indoor modelling of a breathing jet. Abstract accepted for the 8th Computational Wind Engineering conference.

4.1 Introduction

Numerically assessing indoor air quality (IAQ), including airborne transmission, has always come with a trade-off between computational cost and accuracy [Kang et al., 2023; Li and Nielsen, 2011]. As building authorities increasingly adopt ventilation-performance regulations, practitioners must employ CFD simulations to numerically iterate over various design solutions for their indoor environments [Leprince et al., 2023a,b; Linares and García, 2019]. To address this challenge, practitioners validate their CFD models to ensure accuracy and quantify uncertainties, enabling more informed decision-making at the early stages of building design.

One of the most widely adopted CFD approaches for building design assessment is the use of steady-state Eulerian-Eulerian Reynolds-Averaged Navier-Stokes (RANS) simulations. This approach employs turbulence models that model the impact of turbulence on mean flow behaviour, while significantly reducing computational cost compared to transient methods such as unsteady RANS, large eddy simulation, and direct numerical simulation. Within the RANS approach, indoor airflow studies have typically used three different sets of physics assumptions to model airflows: 1) isothermal and incompressible flow; 2) thermal and incompressible flow; 3) thermal and compressible flow. The first set is the incompressible, isothermal flow, where density is assumed constant and temperature effects are neglected. These assumptions are appropriate for cases where thermal effects are negligible, or the investigated conditions are isothermal, such as modelling ventilation [van Hooff et al., 2013b; Zhang et al., 2024a], pollutant dispersion [Cao and Meyers, 2015; van Hooff et al., 2013a], or infection risk [Choudhary et al., 2023; Lu et al., 2005]. Rarely have these assumptions been used to model a breathing jet, unless the simulation is conducted in a small space, such as an elevator cabin [Peng et al., 2021], where the ventilation effects are dominant.

The second set of physics assumptions for airflow modelling is incompressible flow with temperature coupling, used for modelling ventilation, thermal comfort, and low-velocity respiratory processes, such as breathing and speaking [Angelova et al., 2021; Ho et al., 2009; Ivanov and Mijorski, 2017; Markov et al., 2019]. These assumptions are typically applied to flows that exhibit low Reynolds numbers (less than 10^4), where density variations are small and arise mainly from temperature differences rather than compressibility. Under these assumptions, the Boussinesq approximation provides an accurate treatment of buoyancy, thermal plumes, and room-scale ventilation at a lower computational cost [Craven and Settles, 2006; Salati et al., 2022]. However, incompressible thermal flow models are sometimes used for more violent respiratory events, such as coughing and sneezing [Bi, 2018; Salati et al., 2022; Shrestha et al., 2024], since incompressible flows are assumed to run at a lower computational cost than compressible

flows.

These more violent respiratory events are more commonly modelled using the third set of assumptions, compressible thermal flow, since the Reynolds numbers of the flows involved are higher than 10^4 , and the exhaled jet produces sharper density gradients [Biswas et al., 2022; Muthusamy et al., 2021; Pendar and Páscoa, 2020]. At these higher Reynolds numbers, compressible flow models are assumed to provide more accurate predictions of jet development, turbulent entrainment, and droplet transport. Similar to incompressible flow models, compressible models are also often used to simulate ventilation [Zhang et al., 2007b], thermal plume [Fredrich et al., 2022], and less violent respiratory events such as breathing or speaking [De Simone et al., 2021; Schmeling et al., 2023]. In these cases, the flow is considered weakly compressible and still requires solving for density variations [Schmeling et al., 2023].

These three set of physical assumptions are thus widely employed to simulate similar respiratory events. While extensive work has been conducted to assess the performance of turbulence models for studying indoor ventilation [Teodosiu et al., 2014; van Hooff et al., 2018] and aerosol dispersion [Owolabi et al., 2023; Zabihi et al., 2025], no systematic evaluation currently exists that compares the three set of physics assumptions in terms of accuracy and computational cost for predicting breathing jets. For example, Limane et al. [2015] has systematically compared incompressible and compressible thermal flows to assess ventilation performance, but has not included the breathing jet. Therefore, this chapter aims to systematically investigate these assumptions to efficiently model breathing jet decay, thereby developing a simplified yet representative approach for incorporating breathing individuals into ventilation simulations during design assessment.

4.2 Experimental and Numerical Methods

4.2.1 Experimental setup

To validate the isothermal incompressible solver when modelling the expiratory breathing jet, we conduct a measurement campaign in the same test chamber used in Chapter 3 at the SenseLab of the Delft University of Technology [Bluyssen et al., 2018]. The test chamber is 3.73m x 2.22m x 2.12m, providing a space for studying mixing ventilation under controlled airflow conditions (see Figure 4.1). Considering the reported higher exposure risk associated with mouth breathing compared to nasal breathing [King Se et al., 2010; Lizal et al., 2020], we focus solely on mouth breathing. Therefore, a polystyrene head manikin with dimensions of 0.3m x 0.22m x 0.15m, breathing through the mouth, stands on a tripod in the chamber (See Figure 4.2). To create a realistic airway in the

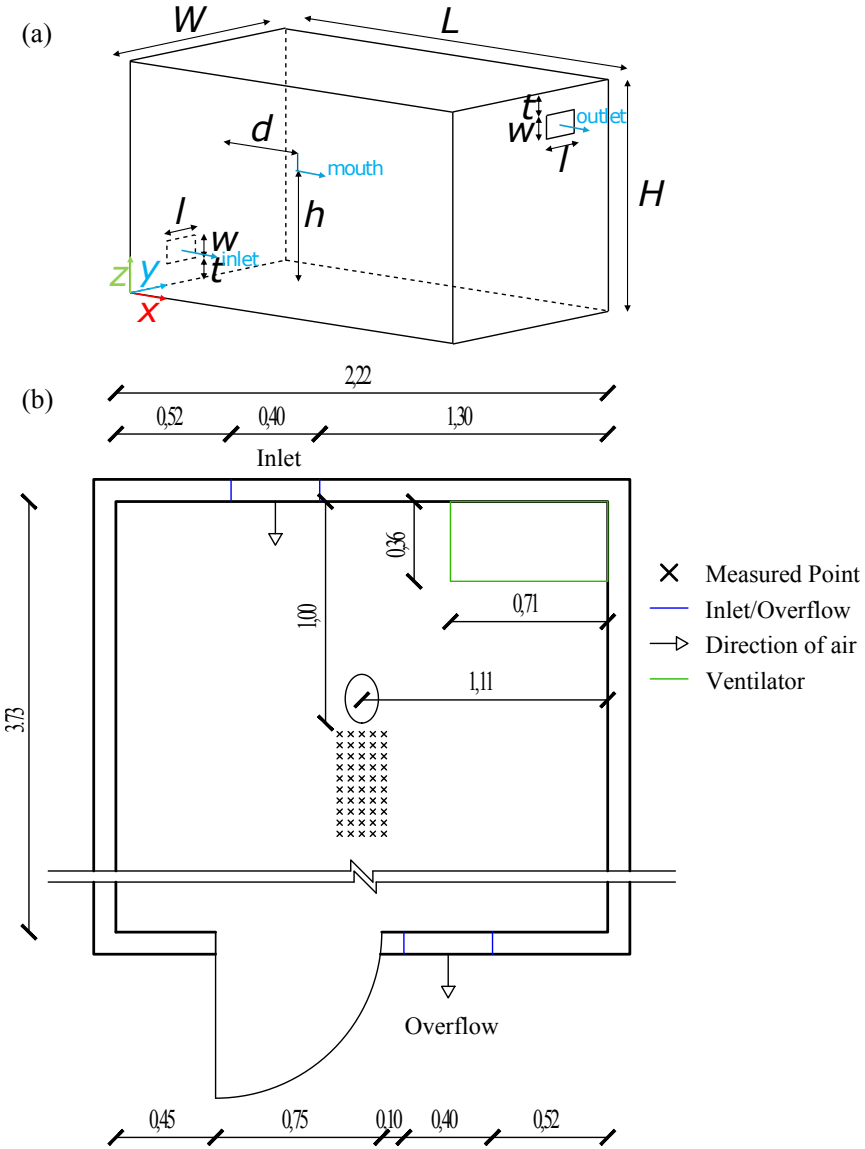


Figure 4.1: (a) Test chamber sketch where L is the length of the chamber, W is the width, H is the height, d is the distance from the mouth the manikin to the back wall, h is the distance from the centre of the mouth to the floor of the chamber, l is the length of the inlet and outlet grill, w is the width of the inlet and outlet grill, and t is the distance from the floor and ceiling of the inlet and outlet respectively, (b) Plan view of the test chamber with the positions of the inlet, outlet, ventilation, breathing head, and measured points.

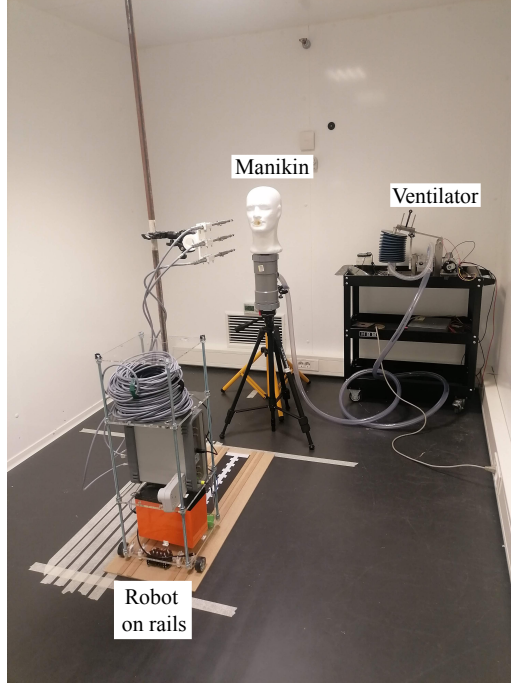


Figure 4.2: Setup of the manikin, the ventilator, and the robot on the rail in the chamber.

polystyrene head, a 3D-printed extruded ellipse measuring 40 mm x 19 mm defines the mouth opening. The ellipse connects to a 15 mm diameter circular tube that extends into the head and into an airway carved in the neck, forming a continuous airflow path inside the manikin (see Figure 4.3). The bottom of the manikin connects to a large PVC container that connects to a mechanical ventilator [Project Inspiration, 2020] through a 48mm diameter tube (see Figure 4.3). We placed the head and the PVC tube to ensure that the centre of the mouth is 1.1 m high from the floor. This setup enables periodic air release from the manikin’s mouth, simulating human expiration.

Experimental procedure

We used Milou (see Chapter 3) on a rail to measure the airflow jet from the manikin’s mouth. To characterise the jet from the mouth, the robot measured the air velocity magnitude along five parallel lines: the centreline of the jet (Line

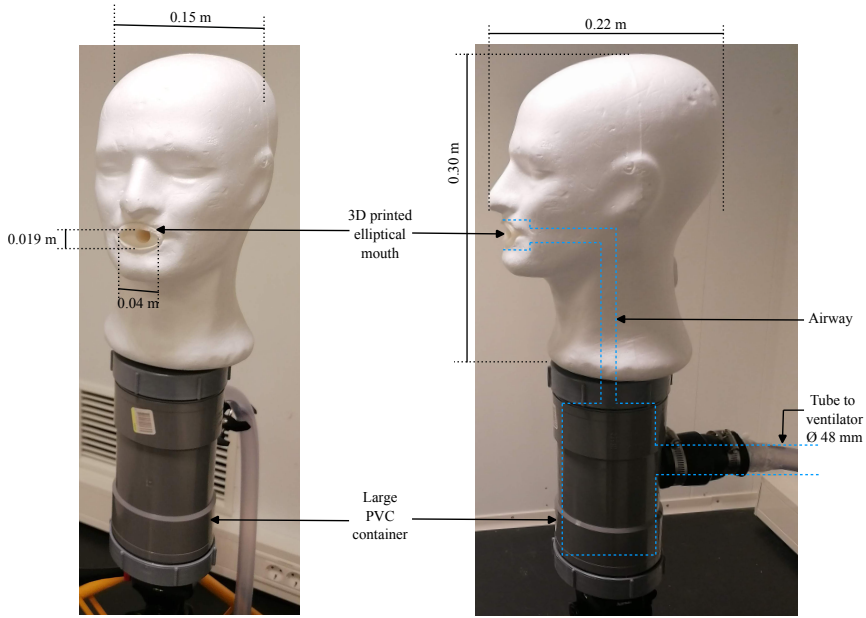


Figure 4.3: Airway from the 3D printed mouth to the connection to the ventilator.

C), two lines offset 5cm to the left (Line B) and right (Line D) of the centreline, and two additional lines offset 10cm to the left (Line A) and right (Line E) of the centreline. We employed three omnidirectional hot-sphere anemometers (Dantec) (see Chapter 3 for specifications) mounted on Milou to measure the air velocity magnitude of the jet (see Figure 4.4 b), as follows:

- probe 1 (p1) placed at 1.05 m, 5 cm below the mouth height.
- probe 2 (p2) placed at 1.1 m, the height of the centre of the mouth;
- probe 3 (p3) placed at 1.15 m, 5 cm above the mouth height.

To capture the spatial evolution of the jet, we measured 10 points at each line where the closest sampling point to the manikin is 5 cm away from the mouth, and each point is 5 cm away from the adjacent points (see Figure 4.4 a). We measured for 5 minutes at each point to capture enough cycles for statistical analysis of the jet.

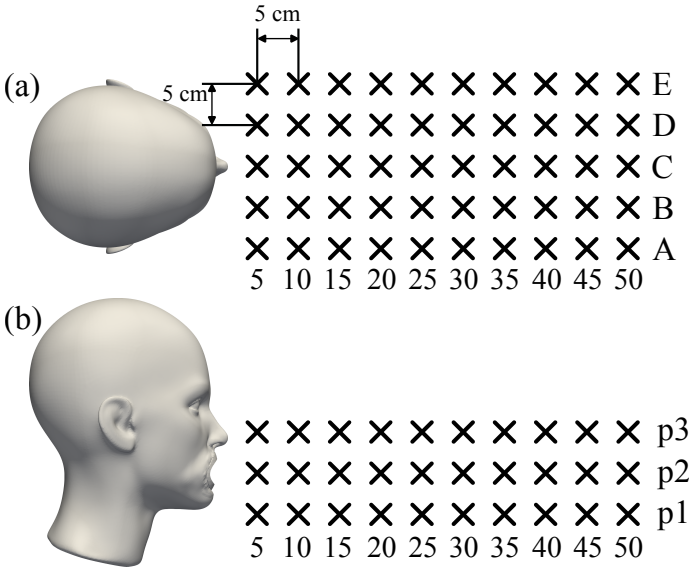


Figure 4.4: Points measured to characterise the expiratory jet from the manikin. (a) is a planar view of the points measured, and (b) is a side view of the points measured showing the three probes' locations.

Non-Dimensional Parameter

Since the available hot-sphere anemometers have a sampling frequency of 2 Hz (see Chapter 3 for more anemometer specifications), which would undersample the normal exhale cycle of 2 s, we developed an approach based on non-dimensional quantities to extrapolate results for CFD validation. To characterise the expiratory flow and get enough sampling points to validate the CFD simulations, we defined the wave Reynolds number (Re_ω), a dimensionless quantity based on the maximum velocity in the exhalation cycle, the characteristic length scale (maximum wave excursion), and the kinematic viscosity of air (ν). The length scale for wave excursion is defined as the ratio of maximum velocity (U_b) to the angular frequency (ω) of the breathing cycle. This definition is expressed mathematically as:

$$Re_\omega = \frac{U_b^2}{\nu\omega} \quad (4.1)$$

In our setup, we customised the camshaft of the original ventilator from [Project Inspiration \[2020\]](#) to better control the exhalation flow rate and achieve the desired wave Reynolds number. We adjusted the motor pump speed so that the exhale cycle is sufficiently long to be properly sampled and the wave Reynolds number matches the human breathing cycle. The ventilator generated a wave Reynolds number of 9.68×10^5 at the manikin's mouth, allowing the parametrisation of the flow.

Figure 4.5 shows the normalised speed measurements of the exhalation at the mouth of the manikin; inhalation (negative cycle velocity) was not included within the breathing cycle. We normalise the speed measurements with respect to the maximum speed at the mouth, $U_m = 2.7$ m/s, and time with respect to the period of one cycle, $t_c = 10.3$ s. The time when the normalised exhalation speed is close to zero is the inhalation time, mimicking an exhalation-breathing cycle. Effectively, the manikin is not inhaling, but the pump is preparing for the next exhalation cycle. The resulting breathing profile of the manikin is a time-dependent sinusoidal function, similar to that of a person [[Gupta et al., 2010](#); [Olmedo et al., 2010](#)].

4.2.2 Numerical setup

Governing equations, turbulence modelling and discretisation schemes

To compare solver performance, we resolve the momentum, energy and passive scalar transport equations using three different solvers in OpenFOAM® ESI 2312 [[ESI-OpenCFD, 2023b](#)]. These solvers correspond to three different physics

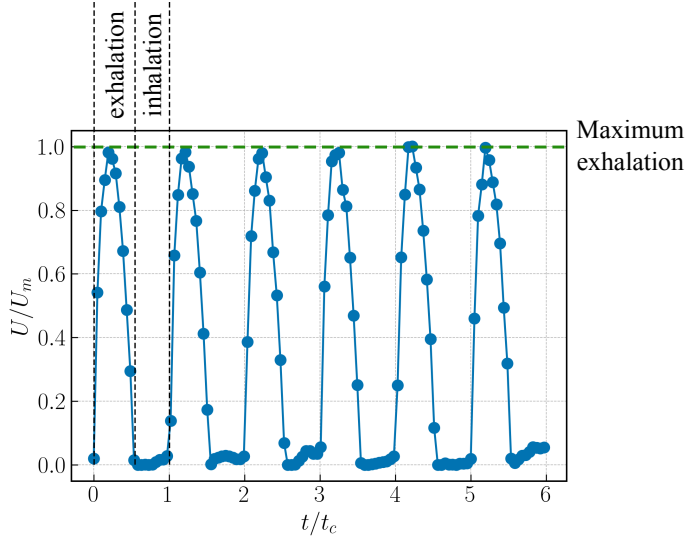


Figure 4.5: Six cycles of measured exhalation speed profile from manikin mouth. U_m is the maximum speed at the mouth, and t_c is the period of one cycle.

assumptions: isothermal incompressible flow, thermal incompressible flow, and thermal compressible flow. For the isothermal incompressible flow assumption, we run a custom simpleFoam solver [García-Sánchez, 2026] using the SIMPLE algorithm, without the energy equation, as the base case, to validate results against measurements in the test chamber and to evaluate the impact of energy on passive scalar transport. For the thermal assumptions, we run two other custom solvers [García-Sánchez, 2026] that treat the coupled phenomena of heat transfer and forced and natural flows in the chamber. To model buoyancy forces, we treat the flow as either incompressible or weakly compressible using a Boussinesq equation of state. All three solvers are customised by adding the passive scalar equation to the existing solvers. Table 4.1 summarises the characteristics of each solver.

Solver	Compressibility	Isothermal
passiveSimpleFoam (pSF)	Incompressible	Yes
passiveBuoyantBoussinesq-SimpleFoam (pBBSF)	Incompressible	No
passiveBuoyant-SimpleFoam (pBSF)	Compressible	No

Table 4.1: The properties of the different solvers used in this study.

4 Exploring the impact of Reynolds-Averaged Navier-Stokes solvers

The equations for mass and momentum used in pSF, are as follows [Greenshields and Weller, 2022]:

$$\nabla \cdot \mathbf{u} = 0 \quad (4.2)$$

where $\mathbf{u}$ is the velocity vector.

$$\mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \nu_{eff} \nabla^2 \mathbf{u} \quad (4.3)$$

where p is the pressure, ν_{eff} is the effective kinematic viscosity given by:

$$\nu_{eff} = \nu + \nu_t \quad (4.4)$$

where ν is the kinematic viscosity ($=1.5 \times 10^{-5} \text{ m}^2/\text{s}$) and ν_t is the turbulent viscosity computed from the turbulence model.

The equations for mass, momentum and temperature conservation used in pBBSF, are as follows [Greenshields and Weller, 2022]:

$$\nabla \cdot \mathbf{u} = 0 \quad (4.5)$$

$$\rho_0 \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho_0 \mathbf{g} [1 - \beta (T - T_0)] \quad (4.6)$$

where ρ_0 is the reference density $= 1.2 \text{ kg/m}^3$, $\mathbf{u}$ is the velocity vector, p is the pressure, μ is the dynamic viscosity derived from the kinematic viscosity ($=1.5 \times 10^{-5} \text{ m}^2/\text{s}$), $\mathbf{g}$ is the gravitational acceleration $= -9.81$ in the domain's z direction, β is the thermal expansion coefficient $= 0.0034 \text{ K}^{-1}$, T is temperature and T_0 is the reference temperature set at 21°C , 294°K .

$$\mathbf{u} \cdot \nabla T = \alpha \nabla^2 T \quad (4.7)$$

where:

- $\alpha = \frac{k}{\rho_0 c_p}$: Thermal diffusivity
- k : Thermal conductivity
- c_p : Specific heat capacity at constant pressure

In addition, for both pSF and pBBSF, we solve a transport equation for the passive scalar for incompressible flow as follows:

$$\mathbf{u} \cdot \nabla \omega_c = D_{eff} \nabla^2 \omega_c \quad (4.8)$$

where ω_c is the passive scalar quantity, and D_{eff} is the effective diffusion coefficient. D_{eff} is the sum of the molecular and turbulent diffusivity coefficient as follows:

$$D_{eff} = \frac{\nu_t}{Sc_t} + D_c \quad (4.9)$$

where Sc_t is the turbulent Schmidt number set at 0.6 [Yimer et al., 2002] and D_c is the molecular diffusivity coefficient set at 1.6×10^{-5} [Roberts, 1972].

The equations for mass and momentum conservation, and the energy conservation equation in terms of the sensible internal energy used in pBSF, are as follows [Greenshields and Weller, 2022]:

$$\nabla \cdot (\rho \mathbf{u}) = 0 \quad (4.10)$$

where $\mathbf{u}$ is the velocity vector and ρ is the density.

$$\nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \rho \mathbf{g} + \nabla \cdot (2\mu_{eff} D(\mathbf{u})) - \nabla \cdot \left(\frac{2}{3} \mu_{eff} (\nabla \cdot \mathbf{u}) \right) \quad (4.11)$$

where p is the pressure and $\mathbf{g}$ is the gravitational acceleration vector set to -9.81 m/s^2 in the vertical direction. The effective dynamic viscosity μ_{eff} is the sum of the molecular dynamic ($\mu = 1.8 \times 10^{-5} \text{ kg/ms}$) and computed turbulent dynamic (μ_t) viscosity and the rate of strain tensor $D(\mathbf{u}) (= \frac{1}{2} (\nabla \mathbf{u} + (\nabla \mathbf{u})^T))$.

$$\nabla \cdot (\rho \mathbf{u} e) + \nabla \cdot (\rho \mathbf{u} K) + \nabla \cdot (\rho \mathbf{u}) = \nabla \cdot (\alpha_{eff} \nabla e) + \rho \mathbf{u} \cdot \mathbf{g} \quad (4.12)$$

where $K \equiv |\mathbf{u}|^2/2$ is the kinetic energy per unit mass and e is the internal energy per unit mass. The effective thermal diffusivity α_{eff} is the sum of laminar and turbulent thermal diffusivities as follows:

$$\alpha_{eff} = \frac{\rho \nu_t}{Pr_t} + \frac{\mu}{Pr} \quad (4.13)$$

where Pr is the Prandtl number set at 0.7 and Pr_t is the turbulent Prandtl number set at 0.85 [Owolabi et al., 2025; Srebric, 2000].

In addition, we solve a transport equation for the passive scalar for compressible flows as follows:

$$\nabla \cdot (\rho \mathbf{u} \omega_c) = \nabla \cdot (\rho D_{eff} \nabla \omega_c) \quad (4.14)$$

We model turbulence using the shear stress transport (SST) $k-\omega$ model [Menter, 1994], which provides accurate near-wall resolution while maintaining robustness in the free stream region. Compared to other turbulence models, $k-\omega$ SST has shown greater performance in modelling breathing jets in the near-wall region

[Aganovic et al., 2019; Owolabi et al., 2025; Zong et al., 2023] as well as in modelling temperature and stratification [Arpino et al., 2022; Park et al., 2025; Pei and Rim, 2021; Wang et al., 2012]. We initiate the inflow boundary conditions for the turbulent kinetic energy, k , and the specific dissipation rate, ω , with the following equations:

$$k = \frac{3}{2} (I|u_{ref}|)^2 \quad (4.15)$$

where I is the turbulence intensity set at 10%, and u_{ref} the reference velocity at the mouth.

$$\omega = \frac{k^{0.5}}{C_\mu^{0.25} L} \quad (4.16)$$

where C_μ is a constant equal to 0.09, and L is the reference length scale, which is the mouth opening width of 0.04 m. We ran all cases for 50,000 iterations to ensure convergence. We also chose second-order upwind discretisation schemes for the velocity divergence, and linear interpolation schemes for gradient calculation.

Computational domain and initial boundary conditions

The computational domain represents a replica of the chamber used for the validation setup. The domain's dimensions are thus equal to those of the chamber

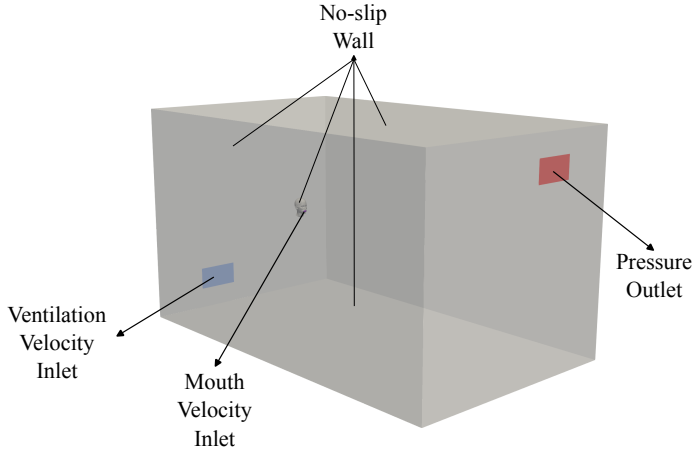


Figure 4.6: Computational domain and boundary conditions for the CFD simulations.

from the experimental setup ($L = 3.73\text{m}$, $W = 2.22\text{m}$, $H = 2.12\text{m}$) (see Figure 4.1 (a)). The exhalation from the mouth is the source of heat in the system.

We set the exhalation temperature to 310 K [Wei et al., 2022] and the background room air temperature to 294 K, based on measurements from the experimental setup. We assume all walls are adiabatic. For the mouth velocity, we average the measurements at the mouth (see Figure 4.5) and set the inlet velocity at the mouth to 0.55 m/s. For the ventilation case, the inlet velocity is set at 0.7 m/s based on nine sampled points at the inlet in the chambers. In the no-ventilation case, we introduce infiltration to represent air leakage into the test chamber. Air leakage is a source of uncertainty in indoor simulations, especially in the absence of ventilation, where small infiltration flow can significantly influence the indoor airflow field [Eom and Kang, 2025; Park et al., 2021]. Therefore, we conducted a series of simulations with different inlet velocities ranging from 0.025 m/s to 0.2 m/s and compared the results to our measurements. As a result, we chose 0.15 m/s for the inlet velocity for the no-ventilation case. For the passive scalar, we prescribe a normalised, dimensionless reference concentration of 1 at the manikin’s mouth, allowing the results to be interpreted independently of the imposed inlet concentration.

4.2.3 Grid Convergence

For the grid convergence study, we run three meshes with a refinement ratio of 1.31, with an average y^+ value near the head of less than 1 for all meshes (See Table 4.2).

	Grid size [No of cells]	h_0 [m]
Coarse	564 782	0.031
Nominal	1 284 980	0.024
Fine	2 898 312	0.018

Table 4.2: Computational grids and average cell size (h_0).

We use three refinement levels around the head and four additional refinement levels around the mouth to ensure accurate modelling of the breathing jet without increasing computational cost. We ran the initial mesh design on Snellius and the final simulations presented in this chapter on the Delft Artificial Intelligence Cluster (DAIC).

In indoor studies, two GCI equations exist in the literature, both based on the work of Roache [1997]. In Celik et al. [2008], Equation 4.17 normalises the difference between the field from the nominal and the fine mesh with the value from the fine mesh. This equation assumes that field values are not close to zero to normalise the difference between the nominal and fine meshes. However, because indoor ventilation operates at low Reynolds numbers, which produce regions of very low velocity, Equation 4.17 can become unstable for fields such

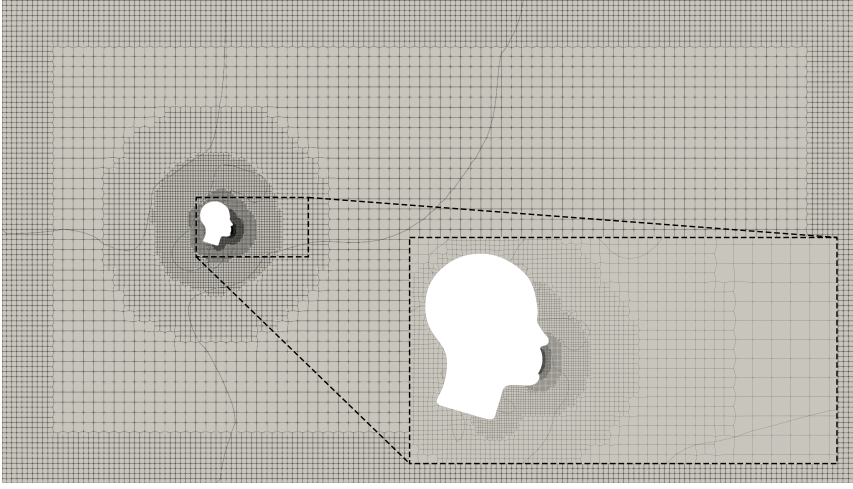


Figure 4.7: Cross-section of the computational grid of the test chamber with detail of the mesh around the manikin head

as velocity or turbulent kinetic energy. Therefore, [Serensen and Nielsen \[2003\]](#) introduced a non-normalised GCI (see Equation 4.18). Without normalising the difference between the two meshes, we avoid dividing by near-zero numbers that produce very large GCI values. To determine which equation is more suitable, we examine the practical differences between the two GCI equations and assess their suitability for evaluating grid convergence across the different fields considered in breathing jet modelling.

$$GCI_{21} = \frac{1.25 \left| \frac{\phi_2 - \phi_1}{\phi_1} \right|}{r_{21}^p - 1} \quad (4.17)$$

$$nGCI_{21} = \frac{1.25 |\phi_2 - \phi_1|}{r_{21}^p - 1} \quad (4.18)$$

where GCI_{21} is the normalised fine-grid convergence index, $nGCI_{21}$ is the non-normalised fine grid convergence index, ϕ_1 and ϕ_2 are the solution of the variable of interest at the fine and nominal grid respectively, p is the apparent order of the method, and r_{21} is the grid refinement factor.

4.2.4 Validation from literature

Since the ventilator we use only regulates the velocity at the mouth of the manikin head, we refer to the literature to validate air velocity, passive scalar transport, and temperature in a buoyant breathing jet. First, we compare our results to the theory of decay in the centreline of a free turbulent jet (see Chapter 2). A free turbulent jet is divided into three zones: a potential core region near the source, a transition region, and a fully developed region where the flow becomes self-similar [Pope, 2000]. Within the self-similar zone, the centreline velocity decreases inversely with distance from the source according to Equation 4.19:

$$\frac{u_x}{u_0} = K_v \left(\frac{x}{\sqrt{A_0}} \right)^n \quad (4.19)$$

where u_x is the peak velocity at a horizontal distance from the manikin's mouth in m/s, u_0 is the initial velocity of a jet and peak velocity in the manikin's mouth in m/s, K_v is the dimensionless centre velocity decay constant for a jet, x is the horizontal distance in m, A_0 is the opening area of a jet, m^2 , and n is the characteristic velocity component. We extracted the centreline velocity from our simulations along the jet axis for each of the three solvers and evaluated it until the centreline velocity fully decayed. We identified the range of the self-similar region as the longest continuous downstream interval exhibiting linear behaviour in log-log space. Since we are running steady-state simulations, we compare the average velocity rather than the peak velocity at the centreline. The simulated decay rate closest to the theoretical jet decay indicates that the solver's results are consistent with the theory.

In addition to the theoretical jet decay, we compared our results with experimental measurements from Olmedo et al. [2010], which characterise the breathing jet under different ventilation regimes using a breathing thermal manikin. The measurements were conducted in a test chamber with dimensions 4.1m x 3.2m x 2.7m, comparable to the dimensions of the test chamber modelled in this Chapter. The orientation of the manikin and the relative distance to the inlet are also comparable in both cases. While the entire experimental configuration does not exactly match the ventilation regime in this study, such as the exact locations of the inlet and outlet, it represents the closest available dataset reporting detailed centreline velocity and contaminant dispersion decay. We therefore used the experimental data as a reference to evaluate whether the simulated decay rate falls within reported experimental trends. The closest ventilation regime studied to ours is mixing ventilation, and we used those results to compare with our findings. We obtained the centrelines of the exhalation jets shown in Figure 4.8 to compare with the decay theory and Olmedo et al. [2010].

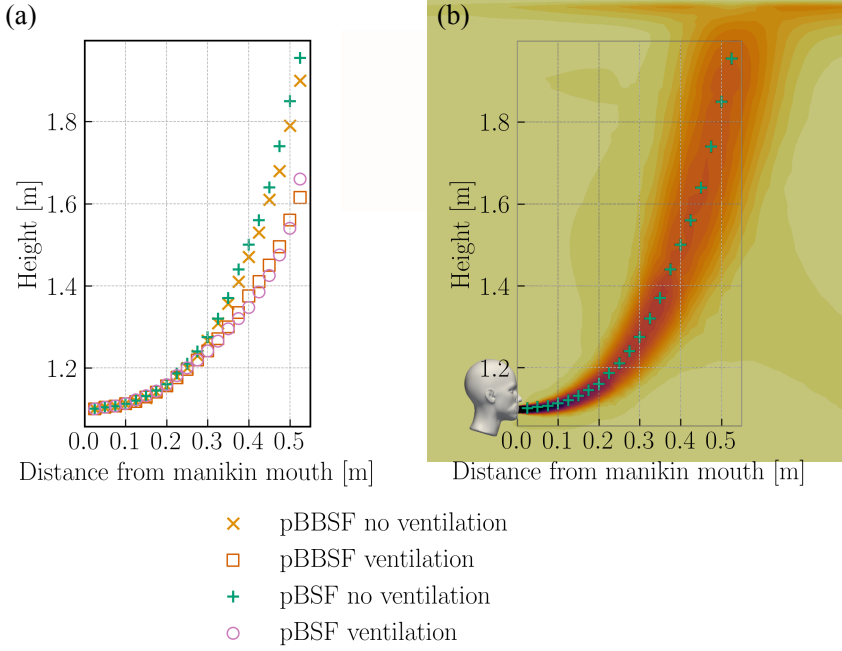


Figure 4.8: (a) Position of points sampled depending on the centreline of the exhalation jets for the temperature solvers with and without ventilation, (b) Overlay of the points sampled on the centreline of the breathing jet of the manikin head.

4.3 Results

4.3.1 Grid convergence

Table 4.3 shows the normalised and non-normalised GCIs of the fields for the three solvers we used. We observe that T , ω , p and w_c have normalised GCI values lower than 5%, whereas the normalised GCI values of U and k rarely drop below 5%. In fact, we have refined the meshes even further than the presented fine mesh in Table 4.2; however, this refinement only led to higher GCI for fields U and k , mainly because finer cells introduced even greater variability in precision error in low-velocity, low-turbulence regions. The reason that U and k values struggle to drop below 5% is the order of magnitude of these fields in an indoor computational domain, which is typically smaller than 0.01 for these fields.

Conversely, T , ω , p and w_c show high non-normalised GCI values, higher than 50%, whereas non-normalised GCI values of U and k are consistently below 5%. T , ω , p and w_c are typically significantly greater than zero, thereby avoiding division by zero in Equation 4.17 and leading to very large nGCI values with Equation 4.18 when not normalised. These differences between normalised and non-normalised GCI values show that these equations should be used appropriately across different fields, depending on the order of magnitude of each field. Based on Table 4.3, we conclude that U and k in indoor simulations, especially in low-velocity, low-turbulence regions, should be assessed using Equation 4.18 and T , ω , p , and w_c should be evaluated using Equation 4.17. We also assume that we have reached grid convergence based on a combination of the two GCIs.

Field	pSF		pBBSF		pBSF	
	GCI_{ext}^{21}	$nGCI_{ext}^{21}$	GCI_{ext}^{21}	$nGCI_{ext}^{21}$	GCI_{ext}^{21}	$nGCI_{ext}^{21}$
U_x	6.5%	1.9%	19.4%	2.9%	10.7%	2.4%
U_y	12.7%	0.5%	28.0%	0.8%	9.9%	0.5%
U_z	7.6%	0.5%	20.4%	1.3%	12.9%	1.0%
U_{mag}	4.2%	1.8%	15.4%	3.0%	5.4%	2.4%
T	-	-	0.0%	75.0%	0.0%	76.1%
w_c	4.5%	2.8%	2.8%	4.4%	0.9%	3.8%
ω	4.9%	256.9%	7.8%	515.4%	3.8%	564.8%
k	12.8%	0.0%	8.6%	0.1%	7.7%	0.1%
p	0.0%	0.0%	0.7%	50.4%	0.0%	50.3%

Table 4.3: Normalised (GCI_{ext}^{21}) and non-normalised ($nGCI_{ext}^{21}$) grid convergence indices for the three solvers

4.3.2 Comparing air velocity magnitude, temperature, and passive scalar transport across the solvers

Figure 4.9 shows the velocity magnitude contour plots at the centre of the test chamber. Without ventilation, in the isothermal, incompressible case (pSF), we observe low-magnitude wall impingement on the opposite side of the breathing jet and along the ceiling. This impingement results from the infiltration velocity set at the ventilation inlet. As the breathing jet develops across the chamber, it bends downward due to floor-level recirculation driven by the small inlet velocity. With the thermal solvers, we no longer observe wall impingement, unlike with the isothermal solver, because buoyancy-driven forces dominate over momentum-driven forces from infiltration. The thermal breathing jets are directed upward due to buoyancy, reach the ceiling, and spread over it. The incompressible thermal jet is wider and dissipates earlier than the compressible thermal jet, highlighting the impact of density variations on jet shape prediction.

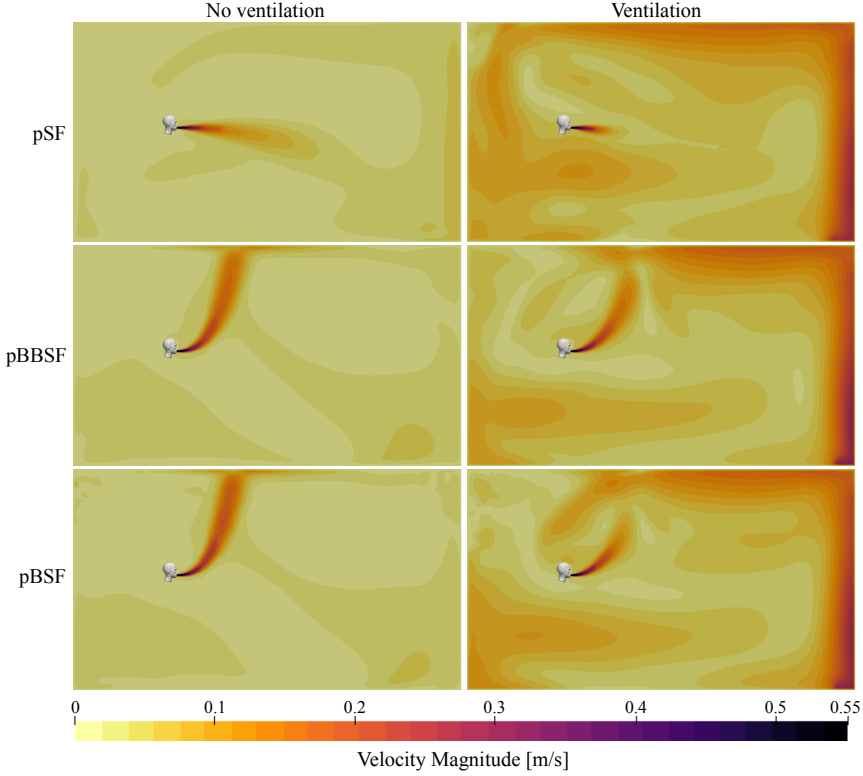


Figure 4.9: Air velocity magnitude of all three solvers at $y = 1.1$, section through the centre of the mouth with and without ventilation.

In all solvers with ventilation, the inlet flow impinges on the wall, where we observe higher velocity magnitudes, then recirculates towards the ceiling. The surrounding airflow in the isothermal, incompressible case (pSF) appears to create a large recirculation flow: after the inlet flow impinges on the opposite wall, it rises to the ceiling, then recirculates behind and under the manikin's head. The jet from the mouth interacts with a stronger surrounding airflow, enhancing mixing and entrainment around the jet. This causes the jet's momentum to spread and decay faster, shortening it compared to the case without ventilation. In the thermal solvers, the jet is directed upward by buoyancy. The interaction between the jet from the mouth and the recirculated airflow at the ceiling is stronger. Both thermal jets are shorter due to the recirculated ventilation flow, but the recirculation airflow is also shorter due to stronger interaction with the jet. In incompressible thermal flow (pBBSF), the breathing jet appears to

almost completely block the flow at the intersection between the recirculation and the jet. The recirculation flow from the ventilation also impacts the fully developed phase of the jet, leading to an earlier terminal phase of the jet. In compressible thermal flow (pBSF), the breathing jet alters the direction of the recirculation flow, pulling it downward into the depression zone it creates. This interaction results in a shorter, thinner jet in the compressible flow compared to a longer, wider jet in the incompressible flow. In both thermal flows, we observe a recirculation zone under the manikin's head, driven by airflow recirculation from the lateral walls.

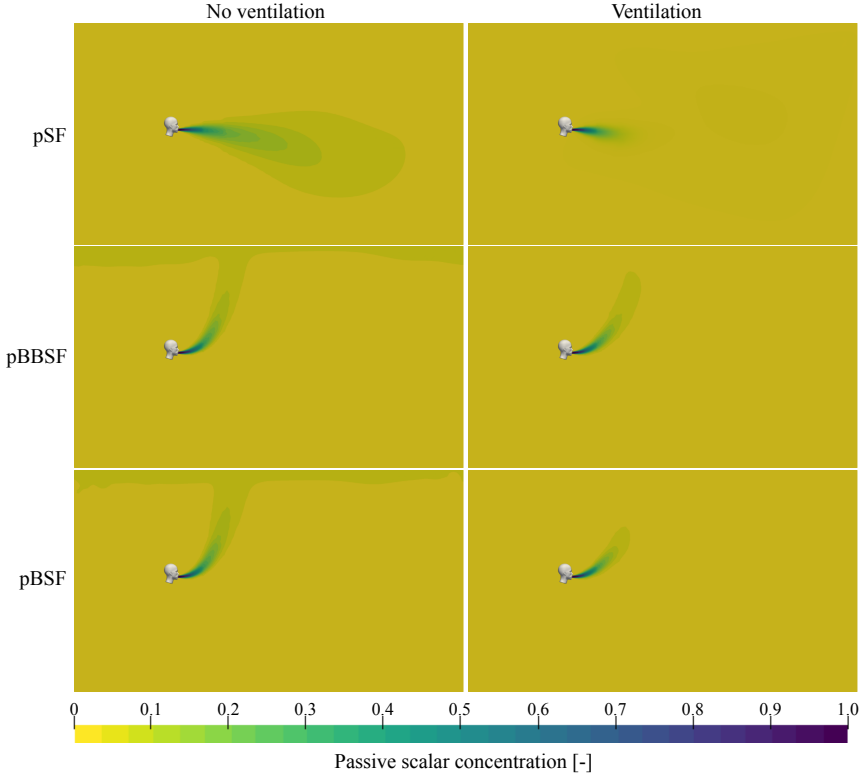


Figure 4.10: Passive scalar concentration of all three solvers at $y = 1.1$, section through the centre of the mouth with and without ventilation.

The passive scalar concentration is determined by the breathing momentum, which, in turn, is influenced by the surrounding airflow momentum (see Figure 4.10). Without ventilation, for isothermal, incompressible flow, the passive

scalar dispersion follows the momentum jet dispersion, with a broader jet due to stronger scalar diffusion. For the thermal flows, the passive scalar jet reaches the ceiling and spreads over it, even though the momentum jet does not spread as much. With ventilation, the passive scalar follows the momentum jet more closely. In isothermal, incompressible flow, a stronger imposed background flow reduces turbulent mixing in the chamber, limiting the diffusion of the passive scalar. For the thermal flows, forced convection dominates over buoyancy, reducing stratification and passive scalar diffusion.

For the thermal flows, temperature is responsible for the upward jet observed in both the momentum and the passive scalar (see Figure 4.11). The incompressible flow appears to allow the upward temperature jet to spread more along the ceiling than in the compressible flow. This difference is due to how temperature is modelled in both cases. In the incompressible case, only temperature affects buoyancy through the Boussinesq approximation. However, in the compressible case, density variations affect all governing equations, altering local ceiling and global flow structures.

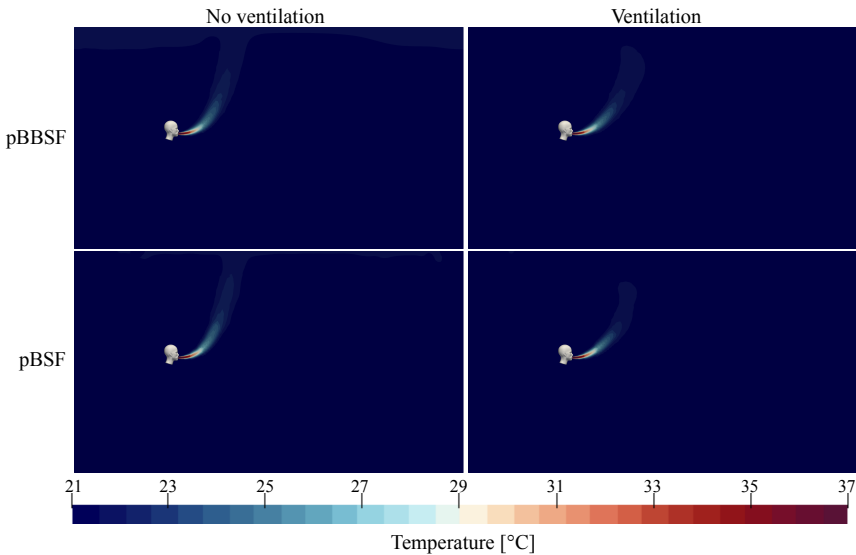


Figure 4.11: Temperature of the thermal solvers at $y = 1.1$, section through the centre of the mouth with and without ventilation.

4.3.3 Validation

Comparison to anemometer air velocity magnitude measurements

To validate the pSF solver, we compare our results with our experimental data in the test chamber. Figures 4.12, 4.13, and 4.14 show the air velocity magnitude from the measurements and the simulations at probes 1, 2, and 3, respectively. Qualitatively, the CFD simulations reproduce the general mean flow structures observed in the experimental data: a central jet core and lateral spreading regions that decay away from the core, both laterally and longitudinally, from the mouth. We also observe that in the lateral spreading regions, the jet develops further away from the mouth. However, a closer look reveals that, where the air velocity magnitude drops below 0.05 m/s, there is almost no agreement between the experimental data and the CFD results (see Figures 4.12, 4.13, and 4.14). Our CFD results thus underestimate the jet's span width, consistent with the tendency of RANS simulations to inaccurately model the jet's wake compared to its centreline. Another issue with the low air velocity magnitude values and numerical simulations is the presence of near-zero values, as seen in the GCI calculations. The near-zero values can cause precision errors, resulting in discrepancies with the experimental data. Additionally, the measurement equipment's threshold is set at 0.05 m/s, which compromises the accuracy of the experimental data at values below 0.05 m/s.

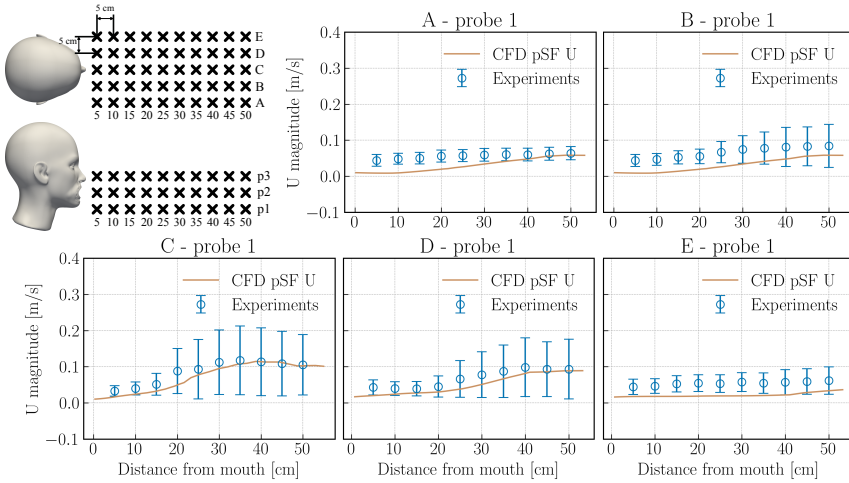


Figure 4.12: Air velocity magnitude near the mouth of the manikin of passiveSimpleFoam (pSF) at probe 1

4 Exploring the impact of Reynolds-Averaged Navier-Stokes solvers

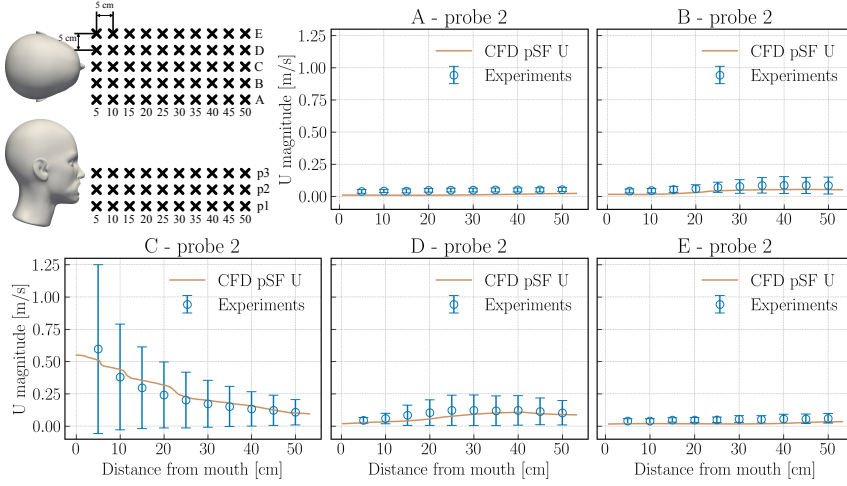


Figure 4.13: Air velocity magnitude near the mouth of the manikin for passiveSimpleFoam (pSF) at probe 2

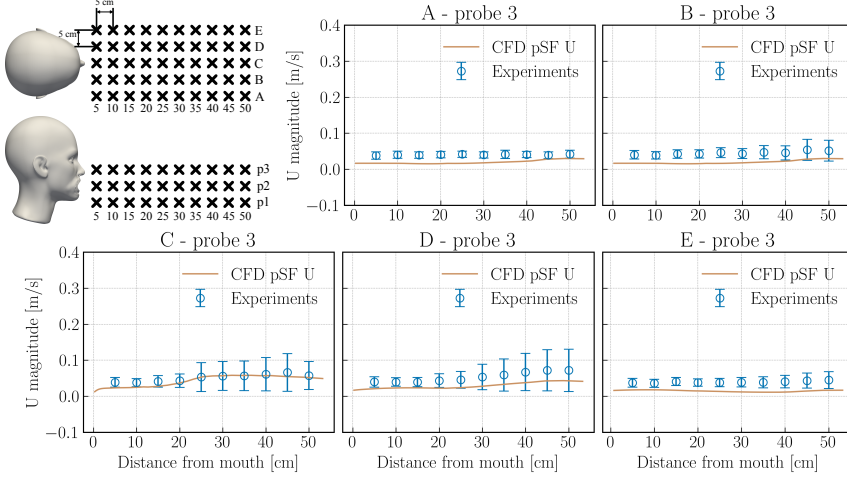


Figure 4.14: Air velocity magnitude near the mouth of the manikin for passiveSimpleFoam (pSF) at probe 3

To quantitatively assess agreement between the experimental data and the CFD results, we compute the R^2 value, which yields 0.83, indicating good agreement with experimental data, despite the CFD results underpredicting in the decaying regions. Moreover, the largest difference in those regions (0.04 m/s) is lower than 10% of the initial velocity at the mouth. Consequently, the pSF solver is validated.

Comparison of thermal solvers to literature measurements

Velocity magnitude and passive scalar concentrations exhibit the most significant differences across the two thermal solvers, while temperature differences do not exceed 2 °C (see Figure 4.11). Therefore, we will focus on comparing and validating velocity magnitude and passive scalar concentrations (See Figures 4.15). Both the compressible (pBSF) and incompressible (pBBSF) temperature solvers capture a similar centreline decay of the jet and passive scalar concentration. The biggest difference is seen after a normalised distance of $10D^*$ in the terminal region of the jet, both with and without ventilation, although it is larger between pBBSF and pBSF with ventilation on, highlighting the impact of compressibility on the background flow and its interaction with the breathing jet, as we saw in Section 4.3.2. Compared with Olmedo et al. [2010], the air velocity magnitudes are in agreement with our CFD results. The contaminant and the passive scalar concentration decay differently because passive scalar transport is more sensitive to the airflow in the room, which differs between the two cases. Since the velocity magnitude is in good agreement with the measurements, we consider our thermal solvers validated.

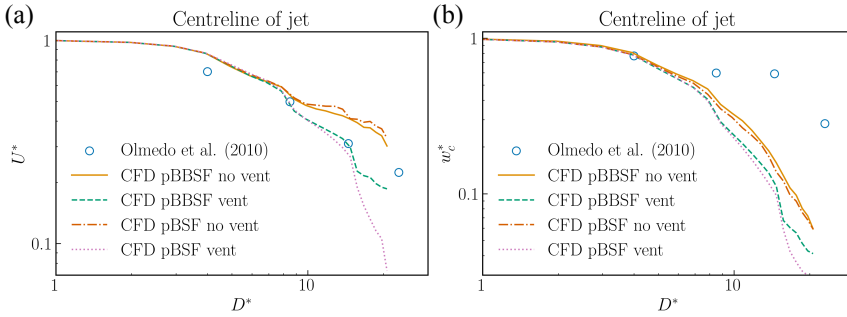


Figure 4.15: (a) Normalised air velocity magnitude (U^*) compared to Olmedo et al. [2010] (b) Normalised passive scalar concentration (w_c^*) compared to Olmedo et al. [2010]. D^* denotes the normalised distance.

Comparison to the jet decay theory

In the self-similar region of a turbulent free jet, the centreline velocity decays according to a power-law whose exponent depends on the jet's effective dimensionality. A plane jet exhibits a centreline decay of approximately $U_c \sim x^{-1/2}$, whereas a three-dimensional jet follows a steeper decay $U_c \sim x^{-1}$. Consistent with this jet decay theory, the no-ventilation cases show a velocity magnitude decay exponent close to -0.5, indicating behaviour similar to that of a plane free jet, likely due to the lack of surrounding turbulence suppressing lateral jet spreading. In contrast, the ventilation cases show a velocity magnitude decay exponent close to -1, identical to that of a three-dimensional jet [Nielsen, 1995; Pope, 2000] (See Table 4.4).

Solver	Ventilation	U slope	w_c slope
pSF	no	-0.59	-0.64
pBBSF	no	-0.52	-1.25
pBSF	no	-0.48	-1.28
pSF	yes	-0.98	-1.08
pBBSF	yes	-0.81	-1.52
pBSF	yes	-1.08	-1.71

Table 4.4: Slope of linear regression at the centreline of the fully-developed jet for the three solvers with and without ventilation.

With respect to passive scalar concentration along the jet centreline, the decay rate only matches the jet decay theory for the pSF solver, with an exponent close to -0.5 for the no-ventilation case and an exponent close to -1 for the ventilation case. Neither the decay from our thermal solvers nor from the experimental measurements of Olmedo et al. [2010] reproduces exponents matching the -1 exponent expected in the self-similar region of the jet. Although the magnitudes of the normalised concentration differ between the datasets, both exhibit substantially different decay than predicted by similarity theory. This suggests that, in the presence of buoyancy-driven forces, the jet decay theory is more applicable to momentum transport than to scalar transport, at least for the breathing jet.

The pSF results, with and without ventilation, are most consistent with the jet decay theory. However, the breathing jet from pSF does not capture the buoyancy effect, an important characteristic of the breathing jet. Therefore, pSF can be used as a reference but should not be used solely to model a breathing jet. For the thermal solvers with ventilation, the pBSF solver best agrees with the theory, with an exponent of -1.08 in the self-similar region compared to -0.81 for pBBSF (See Table 4.4). Instead, in the no-ventilation cases, there seems to be no clear preference between the two thermal solvers. In summary, both pBSF and pBBSF are suitable for no-ventilation cases, whereas with ventilation, pBSF

best characterises the decay of the breathing jet at minimal computational cost (see Table 4.5).

Solver	Ventilation	Run time [hours]
pSF	no	6.60
pBBSF	no	7.81
pBSF	no	8.23
pSF	yes	7.03
pBBSF	yes	7.66
pBSF	yes	7.28

Table 4.5: Run time of the three solvers with and without ventilation.

4.3.4 Limitations and future work

This study has several limitations that should be addressed in future investigations to improve experimental validation. First, validation experiments were conducted using a styrofoam head rather than a thermal breathing manikin. While the current setup allows validating isothermal solvers, it does not allow releasing a thermal breathing jet with aerosols or tracer gas. Additionally, including the ventilator pump and its setup in the room may result in airflow interference. Future work should include measurements in the test chamber using a thermal breathing manikin to validate the thermal solvers.

Second, full velocity vector fields could not be experimentally validated against numerical simulations, as omnidirectional anemometers only measure velocity magnitude. Since flow direction and recirculation patterns play important roles in scalar transport and buoyancy-driven behaviour, future studies should employ measurement techniques capable of quantifying the 3D velocity component. Finally, the available omnidirectional anemometers have a lower threshold of 0.05 m/s, which limits measurement and validation accuracy in low-velocity regions, such as the decaying breathing jet. Future experiments should use equipment with lower thresholds, such as ultrasonic anemometers.

4.4 Conclusion

In this chapter, we systematically assess three solvers that use three different sets of physical assumptions about the airflow: isothermal and incompressible, thermal and incompressible, and thermal and compressible, to determine the impact of these assumptions on the predicted flow behaviour. As observed in the results, although these three sets of assumptions have been used interchangeably to model breathing jets, they exhibit differences in characteristic airflow

patterns and the results they produce. Each type of assumption leads to different interactions between the breathing jet and the background ventilation airflow. Even though isothermal, incompressible flow best matches the jet decay theory, it completely fails to capture the upward trend of a breathing jet in the absence of buoyancy. For thermal flows without ventilation, both compressible and incompressible flows appear to decay similarly. However, with ventilation, thermal compressible flow is preferable to thermal incompressible flow, as it better matches the jet decay theory and accounts for density variations without additional computational cost.

5 The devil is in the details: exploring how furniture's geometric level of detail can impact indoor airflows

Chapter 4 presented the most suitable solver for simulating indoor airflows. However, no standards currently exist that define how to model indoor spaces, specifically the details in the geometries used for indoor airflow and ventilation predictions. When simulating indoor airflow with CFD, researchers often assume varying levels of geometric detail for different surfaces and objects in the room. These choices stem from a lack of geometric data, the required effort to simplify geometry and generated meshes, or a neglect of certain geometry effects. In the literature, modelled room geometry for CFD simulations ranges from basic box models to detailed representations of elements such as furniture and people. Therefore, this chapter proposes a framework for geometric-level furniture detail for indoor airflow and ventilation applications using CFD simulations. We systematically examine how the geometric details of furniture affect predictions of indoor airflow. Depending on the application, this can help engineers make more informed decisions about the details of their geometry in indoor airflow and ventilation simulations.

This chapter is based on the following conference abstract and submitted as a paper for review:

Hobeika, N., Bluyssen, P.M., & García-Sánchez, C. (2025). Defining geometric level of detail of furniture for indoor ventilation. Paper presented at 9th EACWE Conference on Wind Engineering, EACWE2025, Trondheim, Norway.

Hobeika, N., Stoter, J., & García-Sánchez, C. (2026). The devil is in the details: exploring how furniture's geometric level of detail can impact indoor airflows. (under review)

5.1 Introduction

Furniture is a defining feature of most indoor spaces. Tables, chairs, beds, and partitions act not only as functional objects but also as obstacles, altering airflow paths, generating recirculation zones, and influencing where airborne particles and contaminants settle [Hormigos-Jimenez et al., 2018]. These interactions between airflow and furniture in rooms can impact occupant exposure to airborne pathogens. This impact has been previously demonstrated experimentally and numerically in studies that show how furniture arrangements affect airflow velocities, temperature distributions, and contaminant dispersion patterns, with significant implications for infection risk and ventilation efficiency [Haghighat et al., 1996; Hatif et al., 2023; Hormigos-Jimenez et al., 2018; Zhuang et al., 2014].

Despite the evidence of its importance, there is no consensus regarding the level of detail used in furniture geometry within the Computational Fluid Dynamics (CFD) community, where furniture is still frequently simplified or omitted in simulations. Some studies omit furniture entirely, treating indoor spaces as empty volumes, and include only manikins as the occupants of the indoor space [Arjmandi et al., 2022; Ascione et al., 2021; Liu et al., 2021b; Olmedo et al., 2012; Park et al., 2024; Villafruela et al., 2016]. Others adopt simplified representations, modelling furniture as cuboid blocks [Hormigos-Jimenez et al., 2018; Lo and Novoselac, 2010; Ren et al., 2022] or simply omitting thin structures such as the legs of tables and chairs [De Simone et al., 2021; Mahmoud et al., 2024; Song and Meng, 2015]. Several other studies include highly detailed furniture geometries [Ang et al., 2023; Hormigos-Jimenez et al., 2018; Kehler et al., 2021; Olmedo et al., 2022; Zhuang et al., 2014]. The geometric representation of furniture is often a choice motivated by practical considerations: detailed furniture models complicate geometry processing, make mesh generation more challenging, require a finer grid to resolve small features, and consequently increase computational cost. Furthermore, acquiring accurate 3D furniture geometry can be non-trivial, as laser scans, manually measured dimensions, or computer-aided design (CAD) drawings are not always available.

However, with the growing availability of building information modelling (BIM) models and high-resolution laser scans of indoor environments, it is important to investigate how furniture’s geometric level of detail (fLOD) influences the surrounding indoor airflow in CFD simulations to better design healthy indoor environments. Outside the CFD community, standards and frameworks already define different levels of detail (LOD). First, CityGML 2.0 [Open Geospatial Consortium, 2012] defines multiple levels of detail (LOD 0 to 4) for representing building and city objects, where lower LODs capture coarse block models and higher LODs provide increasingly detailed geometry and semantics. Within this LOD framework, building furniture is modelled in the finest level of detail, LOD

4, with fully detailed geometries. A new version of this standard, CityGML 3.0 [Open Geospatial Consortium, 2021], introduces a more flexible LOD framework in which building furniture is modelled at a detailed geometric LOD when the room is modelled at a high LOD. Another standard, the Indoor Mapping Data Format (IMDF) [Apple Inc. and Open Geospatial Consortium, 2021], represents furniture as simple polygons or footprints with optional height attributes. Although these standards provide some information regarding the level of detail of furniture, they are optimised for indoor positioning, wayfinding, or asset management and do not provide sufficient refinements for furniture geometry in indoor CFD simulations. Other frameworks also define fLOD for other applications, such as the BIM field [BIM Acceleration Committee, 2023], which defines the levels of development, ranging from 100 (conceptual massing) to 500 (as-built), with a focus on geometric accuracy and information reliability for design coordination, fabrication, and installation. For daylight simulation, Forouzandeh et al. [2024] proposes a geometric level of detail based on the oriented bounding box (OBB) of objects, including furniture. While these frameworks represent progress in formalising indoor LOD generally and fLOD specifically, none of the previous definitions based on levels of development or the OBB size aligns appropriately with CFD strategies, because these definitions discard objects based on size or geometric features rather than the extent of their influence on airflow distributions.

Although refined definitions for representing furniture geometry at different LODs are lacking, there is a clear need for a framework for fLOD tailored to indoor CFD simulations. This need is strongly supported by previous research, which shows that a small change in geometric detail can significantly influence airflow and dispersion predictions when other indoor obstacles, such as manikins, are present. For example, Topp et al. [2003] investigated four different thermal manikins in a seated position in a full-scale test room. The geometric complexity of the manikins ranges from a simple block shape of a seated person to more detailed human-like manikins. The study revealed distinct velocity and concentration profiles away from the manikins, even when the difference was a change in the angle of the torso or the presence of space between the legs while seated. This level of detail would not be relevant to the previous frameworks, but could influence airflow patterns in a room, which motivates the need for guidelines on the geometric complexity of manikins and other indoor obstacles in CFD simulations for different ventilation studies. In another study, Yan et al. [2016] numerically simulated six computational thermal manikins (CTMs): one detailed 3D scanned version and five simplified versions produced by different geometry simplification methods. They simulated airflow and contaminant transport in densely occupied indoor spaces, such as aeroplane or train cabins, where the number of CTMs is high. They demonstrated that simplifications to CTMs can significantly influence contaminant distribution predictions and concluded that mesh decimation is the simplification method that balances ac-

curacy and computational cost. Similarly, Mazumdar et al. [2011] investigated three CTMs (rectangular, cylindrical, human-cuboid) in an airline cabin and found that the shape of the manikin does impact the contaminant concentration distribution. Additionally, Zhang et al. [2025] numerically studied two levels of detail of manikins, one cuboid-shaped and one human-like, in a hospital setting between a patient on a bed and a doctor examining that patient. The level of detail of the doctor manikin impacted the risk of infecting the patient, proving the importance of understanding the level of detail of indoor obstacles. Yet no similar studies systematically examine different fLODs and their impact on the simulated surrounding airflow. Given the role of furniture in shaping airflow and contaminant and airborne particle dispersion, the absence of a fLOD for indoor CFD studies can hinder the accurate prediction of ventilation effectiveness and risk assessment. To address this limitation, this paper proposes a fLOD framework for indoor CFD studies and tests its relevance through a classroom-like case study under two ventilation regimes: mixing and displacement ventilation. The aim of this chapter is to compare the resulting airflow patterns of the different proposed fLODs to each other to understand how different geometric details impact the simulated airflow.

5.2 Methods

5.2.1 Proposed furniture level of detail (fLOD) framework

We develop a fLOD definition framework that distinguishes between three types of geometric features relevant to airflow, block, planar, and linear features, to model furniture. We define the framework with increasing geometric detail, as follows:

1. fLOD 0 contains no furniture and acts as a reference without furniture.
2. fLOD 1 models the furniture as blocks with no detail, using the oriented bounding box of the original geometry.
3. fLOD 2 excludes the linear thin structural elements of the furniture, such as arms and legs of tables and chairs, and only represents the planar elements, such as the table top or chair seat.
4. fLOD 3 excludes very small details of the furniture, such as screws, but maintains the defining linear and planar elements of the furniture.

Choosing the appropriate fLOD is done using a decision tree that identifies the user's need for the level of detail (See Figure 5.1 (a)).

fLOD 1 is the most abstracted form of the furniture. Each furniture item is represented by its oriented bounding box, the smallest rectangular cuboid that

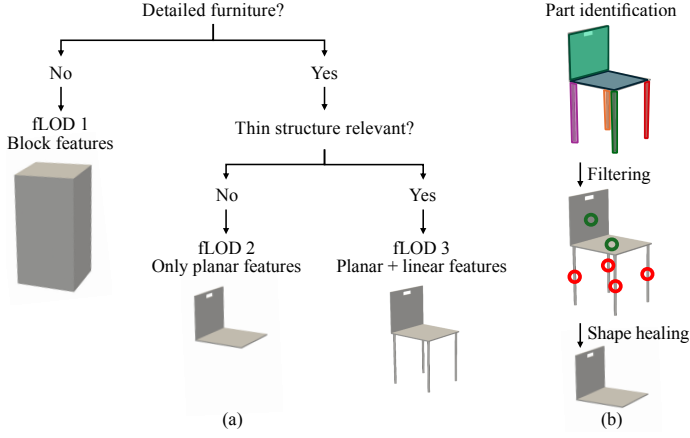


Figure 5.1: (a) Decision tree for choosing the appropriate fLOD. The illustrated example is the fLOD framework of a given table. (b) Part-based simplification of the table.

encloses it. This representation preserves the furniture’s global dimensions and orientation while eliminating all finer features. For fLOD 2 and 3, we apply a part-based simplification to the most detailed furniture representation to remove thin features (See Figure 5.1 (b)). This simplification is implemented as a three-step process: part identification, filtering, and shape healing. Part identification distinguishes between planar and linear features. For the table in Figure 5.1 (a), the part identification results in two part types: planar features, such as the table top, and linear features, such as the legs and their horizontal supports. For the filtering step, each identified part is projected onto the three axis-aligned planes of its oriented bounding box. If any of the three projections fit, a circle with a given diameter ($\delta = 10cm$ for fLOD 2 and $\delta = 1cm$ for fLOD 3), the part is preserved; otherwise, it is filtered out. The chosen thresholds aim to filter out linear features for fLOD 2 and to filter out very small details, such as screws, for fLOD 3. If the resulting geometry is not watertight, shape healing repairs the filtered parts by filling any holes caused by the filtering step, making the geometry suitable for CFD simulations. We have implemented this procedure as an open-source proof-of-concept algorithm to automate the generation of the fLODs from a mesh (see B.1 and the implemented code in Hobeika et al. [2026b]).

5.2.2 Case study

To quantify differences in impact between the fLODs and assess whether the framework is relevant for indoor airflow applications, we run CFD simulations

with the different fLODs for chairs and tables in a classroom setting, including breathing manikins. The geometries in this study are a replica of the Experience room in the Senselab at the Delft University of Technology (6.1 x 4.2 x 2.7 m) [Bluyssen et al., 2018]. Consequently, we focus on two ventilation regimes available within the Experience room: mixing and displacement ventilation. Figure 5.2 shows that four grilles distributed evenly across the room’s ceiling act as an inlet for mixing ventilation and as an outlet for displacement ventilation. Additionally, two grilles in the plinth on the two short sides of the room serve as outlets for mixing ventilation and as inlets for displacement ventilation.

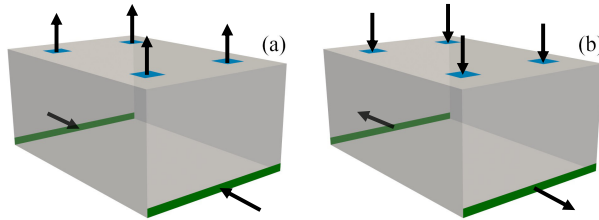


Figure 5.2: Ventilation strategies studied - (a) displacement ventilation, (b) mixing ventilation, with the blue ceiling square grilles and green plinth grilles.

To include dispersion distribution of, for instance, aerosols from breathing people, we place passive scalar sources in the room, as follows:

- One manikin head in the room with an ellipse mouth as a source of passive scalar concentration (see Figure 5.3 (a, b, c, d)). This serves as an ideal reference for furniture analysis.
- 12 full-body manikins adapted from the model in Nielsen et al. [2003] with an ellipse mouth as the source (see Figure 5.3 (e, f, g, h)). This allows us to include the highest level of realism within the manikin representation.
- 12 block full-body block manikins with a rectangular mouth as the source (see Figure 5.3 (i)). This allows us to compare with lower abstraction in the manikin geometries.

We did not include simulations with lower manikin abstraction and higher fLOD, since meshing at such high fLOD would still be dominated by the smallest furniture details, which would not support the choice of a lower abstraction for the manikins. Accordingly, our focus is on isolating the impact of furniture, as previous studies have already established how manikin geometry influences air-flow patterns. To support this objective, we systematically evaluate the different fLODs by cross-comparing the CFD results pairwise and subtracting the results for each unique pair of fLODs.

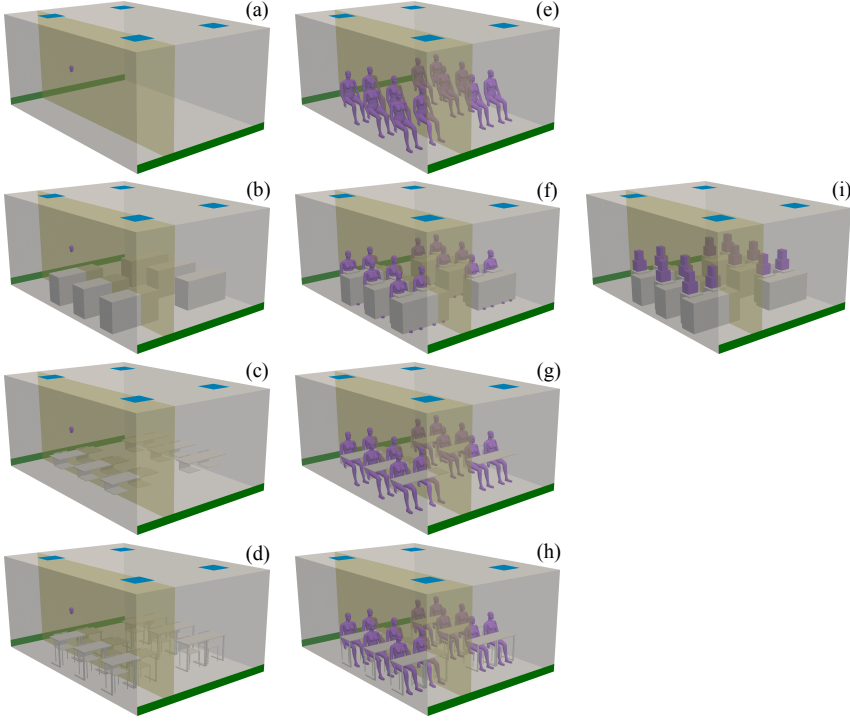


Figure 5.3: The four levels of detail of furniture with head only - (a) fLOD 0, (b) fLOD 1, (c) fLOD 2, (d) fLOD 3. The four levels of detail of furniture with full body manikins - (e) fLOD 0, (f) fLOD 1, (g) fLOD 2, (h) fLOD 3, and (i) block manikin with fLOD 1 - the manikins are in purple, furniture and geometry of the room are in grey, the plane where we extract the results is in yellow.

5.2.3 CFD simulation setup

We use OpenFOAM® ESI 2312 [ESI-OpenCFD, 2023a] to solve the steady-state Reynolds-Averaged Navier-Stokes (RANS) equations. We account for buoyancy effects arising from temperature-induced density variations by employing the buoyantSimpleFoam solver with a Boussinesq equation of state, assuming weakly compressible flow, as per the findings in Chapter 4. The solver chosen to perform the simulations was validated against breathing jet experiments (see Chapter 4 and [Hobeika et al., 2026a]). We apply a uniform velocity profile of 0.2 m/s at all ventilation inlet openings, derived from our airflow rate measurements. At the manikin's mouth, we impose a higher uniform velocity of 0.55 m/s to

represent exhalation, based on the average of our anemometer measurements of a breathing cycle from a manikin head. We apply pressure outlet boundary conditions at all outlets and enforce no-slip conditions on all solid surfaces. For thermal boundary conditions, we specify a fixed temperature of 21°C at the inlets and 37°C at the mouth [Brohus, 1997]. For the passive scalar, we prescribe a reference concentration of 1 at the manikin’s mouth. We discretise the convective terms of momentum, turbulence, energy, and scalar transport equations using second-order schemes. Each simulation runs for 50,000 iterations to ensure all residuals reach a steady state for all cases.

We generate an unstructured computational mesh using snappyHexMesh for all three cases to accurately represent the complex indoor geometry without incurring additional computational cost (See more details in Table 5.1 and Figure 5.4). We apply the finest mesh refinement around the manikin’s mouth and body to capture the higher velocity, temperature, and scalar gradients. We also apply mesh refinement around the inlet and outlet boundaries, the furniture, and the room walls, achieving an average wall-normal resolution of $y^+ \leq 1$ on all solid surfaces.

fLODs	Number of cells		
	Head only	Full body	Block full body
fLOD 0	7 918 261	30 125 671	-
fLOD 1	12 263 602	25 952 875	24 344 531
fLOD 2	12 133 999	30 902 819	-
fLOD 3	13 990 616	31 641 119	-

Table 5.1: Computational grid sizes for the different fLODs.

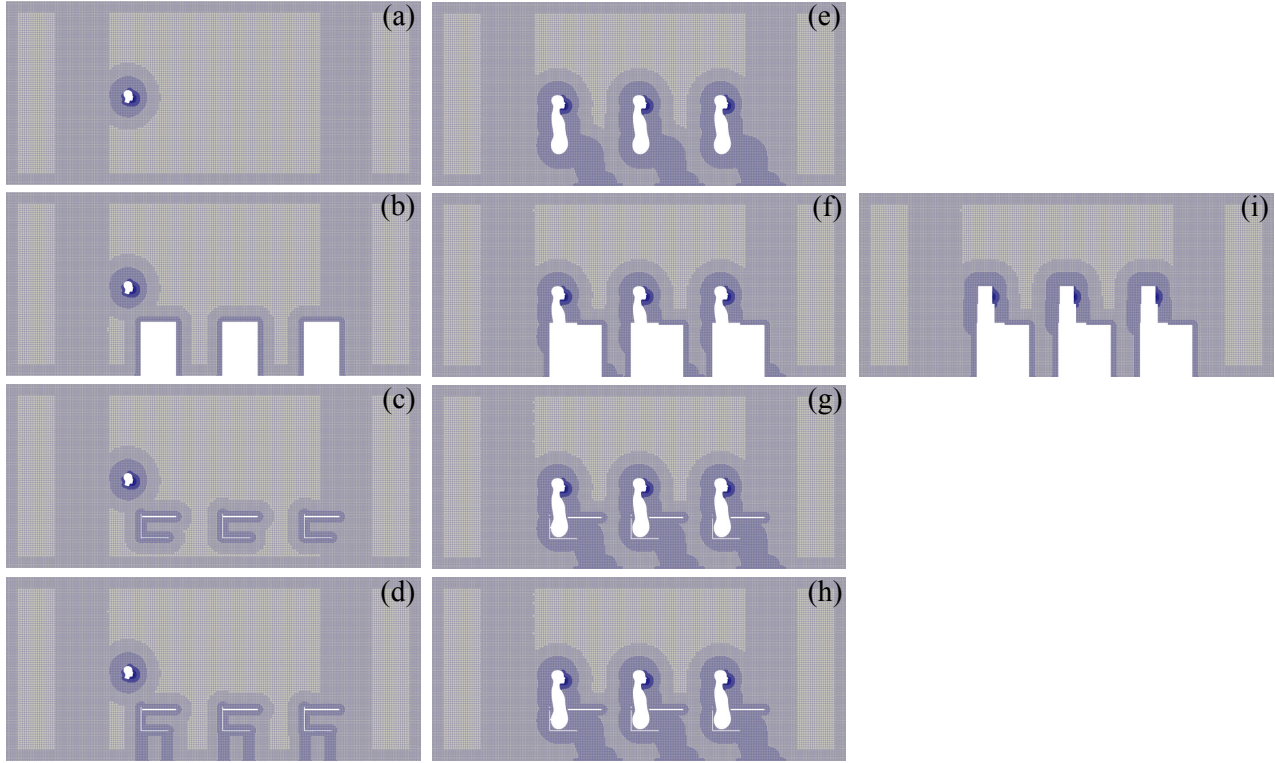


Figure 5.4: Head only case meshes over the fLODs - slice taken at the centre of the mouth - (a) fLOD 0, (b) fLOD 1, (c) fLOD 2, (d) fLOD 3. Full body case meshes over the fLODs - slice taken at the centre of the mouth of manikins close to the aisle between the tables - (e) fLOD 0, (f) fLOD 1, (g) fLOD 2, (h) fLOD 3 and (i) fLOD 1 with block manikins.

5.2.4 Grid convergence

Indoor airflow is characterised by predominantly low velocities and weak turbulence, with certain quantities, such as velocity (U) and turbulent kinetic energy (k), approaching near-zero magnitudes. Although these quantities are not strictly zero in the numerical solution, their values lie close to the limits of numerical precision. As a result, relative comparison between meshes for grid convergence can be misleading, since ratios of near-zero values may yield artificially large differences that do not reflect meaningful physical variation [Serensen and Nielsen, 2003]. Therefore, to verify the grid convergence for the head and full-body cases, we compute the fine grid convergence index (GCI_{ext}^{21}), using two definitions available in the literature: $nGCI_{21}$ from Equation 4.18 for U and k fields and GCI_{21} from Equation 4.17 for all the other computed fields. We chose to run the study for fLOD 2 in both the head-only and full-body cases with mixing ventilation because this fLOD corresponds to the coarsest cells in the vicinity of the furniture area, and the mixing ventilation case is numerically stiffer, with lower velocities in the domain than in the displacement ventilation case. Achieving grid convergence at this level implies that the other fLODs with finer grids near the furniture will inherently satisfy convergence criteria. We measure the solved variables of velocity, pressure, passive scalar, and turbulence quantities at 100 random points in the room. Table 5.2 shows the median GCI_{ext}^{21}

GCI_{ext}^{21}	Head-only case	Full-body case
U_x	2.4%	2.0%
U_y	1.6%	2.5%
U_z	2.6%	1.6%
U_{mag}	3.0%	2.3%
T	0.0%	0.0%
w_c	4.6%	2.3%
ω	6.9%	6.9%
k	0.0%	0.0%
p	0.0%	0.0%

Table 5.2: Median GCI values between medium and fine meshes for the head-only case and the full-body case.

computed for the two cases. GCI_{ext}^{21} has a maximum value of 6.9% across all fields, confirming grid convergence and simulation reliability. Zero-value GCI_{ext}^{21} refer to values smaller than 0.1% and are expected for temperature and pressure when using a compressible solver, as these variables have large absolute magnitudes and the discretisation errors are several orders of magnitude smaller by comparison. As for turbulent kinetic energy, GCI_{ext}^{21} also approaches zero because the field itself is already characterised by near-zero values throughout most of the domain.

5.3 Results and discussion

5.3.1 Impact of the fLOD

We compare the fields of air velocity magnitude, passive scalar concentration, and temperature across the four fLODs under both mixing and displacement ventilation modes, using one breathing head in the first case and 12 full-body breathing manikins in the second case. Difference maps quantify the spatial variation of the fields of interest across different fLODs. Our analysis focuses on the impact of the fLOD on two types of flows: the background flow, characterised by low-velocity and large-eddy structures from the ventilation inlets, and the breathing jets, governed by small-scale, high-velocity turbulent structures emanating from the mouth(s).

Air velocity magnitude

The air velocity magnitude and differences fields under mixing ventilation with the head-only case for the different fLODs are shown in Figure 5.5. For the head-only case, under mixing ventilation, we observe the largest differences in the background flow, up to 0.2 m/s (100% of ventilation inlet velocity), at the front desk, particularly under the inlet grill, when comparing the fLODs to fLOD 0 (see Figure 5.5 (b)). Smaller, yet still noticeable differences, up to 0.1 m/s, appear under the furniture for all fLOD differences.

fLODs 1, 2, and 3 clearly disrupt the recirculation from the ceiling inlet, even when comparing fLOD 2 to fLOD 3. fLOD 1, when compared to fLOD 0, 2, and 3, shows the largest altered background flow at the peripheral desks, where the incoming flow from the ceiling inlet grills impinges on the floor, then on the block furniture, and is redirected upward (see Figure 5.5 (a)). fLOD 2 exhibits higher magnitudes in the recirculation zone, displaying an almost identical upward S-shaped structure when compared to fLOD 1 and 3. This similarity between fLOD 1 with block furniture and fLOD 3 with linear structures, when compared to fLOD 2, indicates that although a single linear thin feature imposes minimal disturbance on the mean flow, the combined presence of multiple linear features - in this case, six legs per chair and table - can significantly modify the flow field. Collectively, the furniture legs can increase the effective blockage ratio, acting like a single block obstacle.

In the breathing jet region, we also observe that the presence of furniture, regardless of the level of detail, impacts the formation of the breathing jet, with differences up to 0.2 m/s (36% of the inlet velocity at the mouth). Without any furniture, the jet is closer to the head and the ventilation inlet flow, because of the stronger background flow. With furniture, the jet develops further away

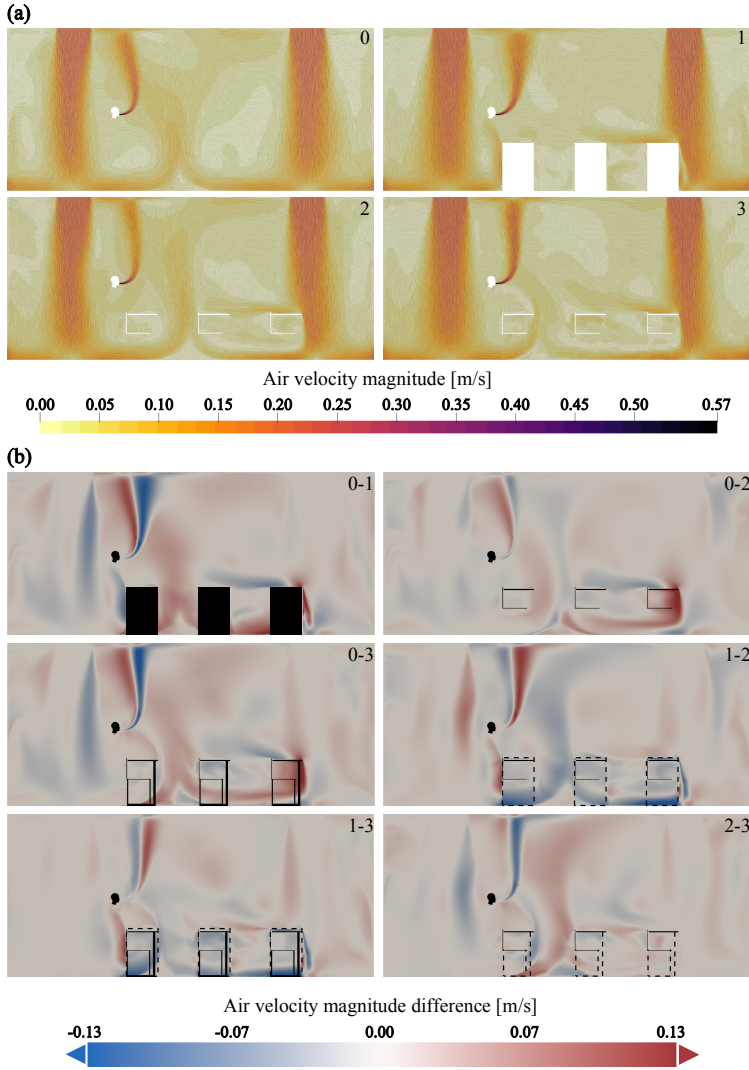


Figure 5.5: (a) Air velocity magnitude under mixing ventilation with the head only case from fLOD 0 to fLOD 3 (b) Air velocity magnitude differences under mixing ventilation with the head only case - scale bar is shown at the 99th percentile for better contrast and text in the top corner is fLODx minus fLODy.

from the head due to the lower impact of the background flow. When comparing fLOD 2 and 3 to fLOD 1, we observe that the jet develops further away from the head with block furniture due to the absence of a strong recirculation zone between the furniture. fLOD 3 also allows a stronger jet to form away from the head for similar reasons, making fLOD 2 the case that blocks the airflow the least.

The air velocity magnitude and difference fields under displacement ventilation with the head-only case for the different fLODs are shown in Figure 5.6. Under displacement ventilation, we also observe differences, up to 0.2 m/s, in the background flow and the jet when furniture is present (see Figure 5.6 (b)). The biggest background flow differences compared to fLOD 1 are at the peripheral desks, similar to mixing ventilation. However, in this case, the differences are at the sides of the desks, where the flow from the plinth impinges on the block desks, creating a strong upward flow in that region (see Figure 5.6 (a)). The differences between the tables are even larger than those in mixing ventilation, primarily because the inlet is now closer to the tables and chairs. Even when comparing fLOD 2 and fLOD 3, we see differences up to 0.2 m/s (100% of the ventilation inlet velocity) in the background flow, especially where the two inlet jets meet. Unlike the mixing ventilation case, the low-level supply airflow directly interacts with the L-shaped table legs. The right inlet jet interacts with two table legs and separates before reaching the left inlet jet. The separation of the right inlet jet allows for the left inlet jet to develop further than in the other fLODs, creating the S-shaped flow pattern and large differences in the background flow (see Figure 5.6 (a)). These differences in inlet jet interactions across the fLODs show that ventilation airflow is sensitive to geometric detail in regions where the supply air is close to furniture, thereby redirecting airflow around the room.

As for the breathing jet, differences reach 0.4 m/s (73% of inlet velocity at the mouth). Differences in the breathing jet between fLODs are greater with displacement ventilation than with mixing ventilation, due to furniture directly between the ventilation inlet and the breathing jet. Another difference with mixing ventilation is that, for fLOD 1, the jet does not develop further from the mouth but instead is directed upwards to the outlet. This change in jet direction is due to the impingement of the inlet ventilation flow on the furniture blocks (see Figure 5.6 (a)). The upward recirculated flow prevents the jet from developing further, resulting in the earlier extraction of the jet. The jet with fLOD 3 extends the furthest because fLOD 3 still blocks more airflow than fLOD 2 and is not as much of an obstacle as fLOD 1, thereby avoiding impingement.

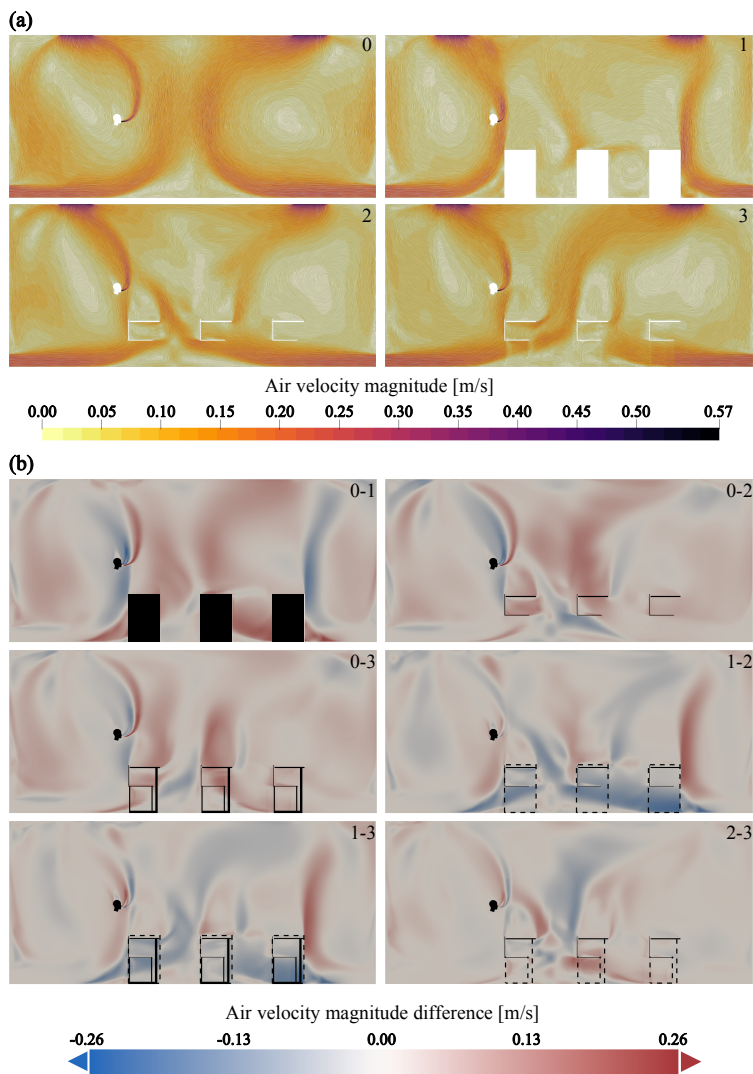


Figure 5.6: (a) Air velocity magnitude under displacement ventilation with the head only case from fLOD 0 to fLOD 3 (b) Air velocity magnitude differences under displacement ventilation with the head only case - scale bar is shown at the 99th percentile for better contrast and text in the top corner is fLODx minus fLODy

Results for the case with full-body manikins under mixed ventilations are shown in Figure 5.7. For this case, we observe the largest differences at the breathing jets, up to 0.17 m/s (31% of inlet velocity at the mouth), when comparing the fLODs to fLOD 0 (see Figure 5.7 (a)). In particular, we observe an inward deflection of the left and middle jets in cases with furniture, i.e., a weak background flow above the furniture, compared to fLOD 0. With weak background flow, the dominant mechanism governing the jet trajectories is mutual entrainment.

Each jet entrains ambient fluid, and the overlapping entrainment zones between the jets produce a pressure deficit in the inter-jet region, which causes the jet profiles to deflect and attract. In the presence of a stronger background flow, i.e., the absence of furniture, the imposed flow at the ventilation inlets supplies momentum to the inter-jet region, reducing the pressure deficit that would otherwise form between the jets. Regarding the right jet, compared to fLOD 0, we observe a smaller profile due to its proximity to the inlet flow, resulting in less impact on the middle jet than on the left jet (see Figure 5.7 (b)). The right jet is, however, impacted by the middle jet, as we also observe an inward deflection of the right jet with the presence of furniture. When comparing fLOD 2 and 3 to fLOD 1, the mutual entrainment between the middle and the right jet is more dominant. The difference between fLOD 2 and 3 is the left jet, where with fLOD 2, the right jet is pulled by the mutual entrainment from the other two jets, whereas with fLOD 3, the right jet seems to form a bigger mutual entrainment with the inlet jet next to it, compared to both fLOD 1 and fLOD 2. This demonstrates how each type of furniture obstacle locally and non-uniformly reduces background flow, affecting the breathing jet at different locations within the room.

Under the furniture, we observe a difference of air velocity magnitude of up to 0.15 m/s (75% of the ventilation inlet velocity). When comparing to fLOD 0, fLOD 1 shows the largest differences between the tables due to the block furniture altering the surrounding airflow. For fLOD 2 and 3, their largest differences relative to fLOD 0 are mostly confined to the areas under the furniture, which is not the case with the head-only results (see Figure 5.5 (b)). This confinement under the furniture indicates that the geometric representation of the manikins under the furniture has a stronger influence on airflow than the geometric representation of furniture legs. We also confirm this interpretation with the small differences between fLOD 2 and 3 under the furniture.

With displacement ventilation, where the inlets are at floor level, and the outlet is at ceiling level, the magnitude of air velocity differences at the breathing jets can reach up to 0.45 m/s (82% of inlet velocity at the mouth). We also observe less mutual entrainment than with mixing ventilation, indicating that the buoyancy effect of displacement ventilation maintains a higher background flow throughout the room (see Figure 5.8 (b)). Compared to fLOD 0, the absence of furniture allows the upward inlet ventilation to immediately exhaust the middle breathing

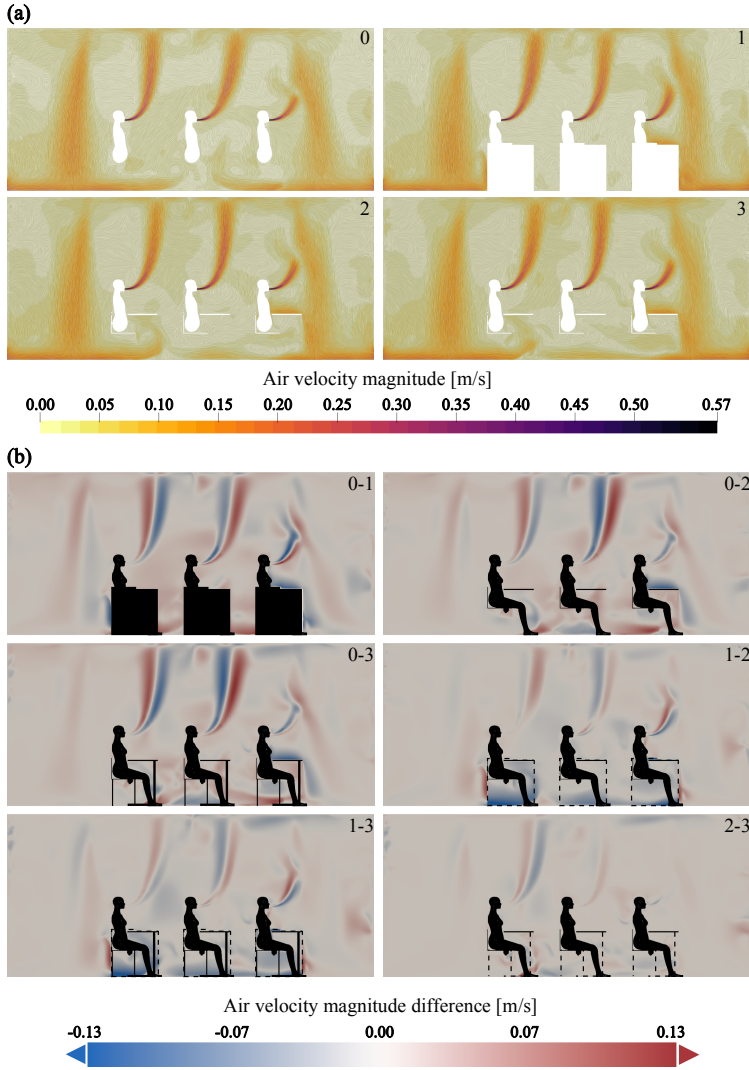


Figure 5.7: (a) Air velocity magnitude under mixing ventilation with the full body case from fLOD 0 to fLOD 3 (b) Air velocity magnitude differences under mixing ventilation with the full body case - scale bar is shown at the 99th percentile for better contrast and text in the top corner is fLODx minus fLODy

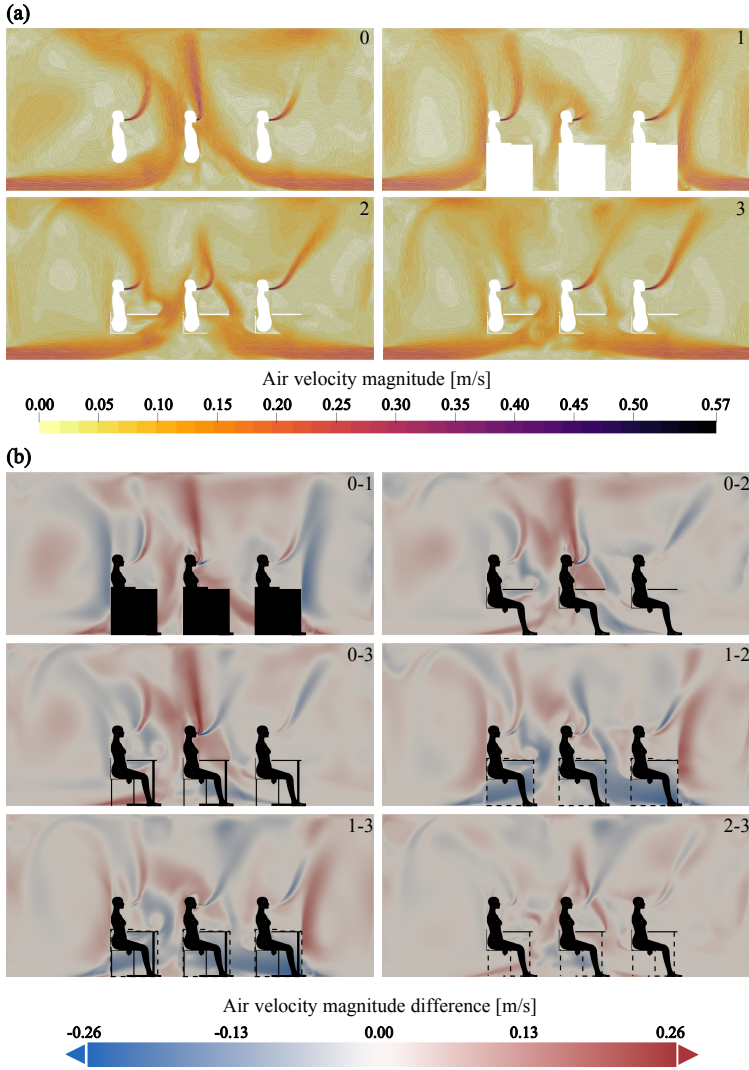


Figure 5.8: (a) Air velocity magnitude under displacement ventilation with the full body case from fL0D 0 to fL0D 3 (b) Air velocity magnitude differences under displacement ventilation with the full body case - scale bar is shown at the 99th percentile for better contrast and text in the top corner is fL0Dx minus fL0Dy

jet, not allowing that jet to further develop in the domain, whereas the right and left jets could develop further away from the mouth in the recirculation areas (see Figure 5.8 (a)). With fLOD 1, we observe a small middle jet, mainly deflected by a strong recirculation airflow from the aisle. The block furniture in fLOD 1 funnels airflow from the plinth inlet grills, creating a stronger flow in the aisle, which is then recirculated to the breathing jets. With fLOD 2, having no obstacles under the tables, more airflow passes through the table surfaces, forcing the middle jet profile upwards rather than towards the exhaust grill above the right manikin. fLOD 3 provides enough obstacles to dilute the flow coming from the ventilation inlets that redirect the middle breathing jet in fLOD 2; however, the linearity of the obstacles does not allow for sufficient funnelling of the airflow, as seen with fLOD 1, thereby allowing the breathing jets to develop further away from the mouth. Similarly to the head-only case, differences in the breathing jets between fLODs are greater with displacement ventilation than with mixing ventilation, due to furniture directly between the ventilation inlet and the breathing jet.

Under the furniture, we observe similar patterns of confinement for displacement ventilation as for mixing ventilation. With displacement ventilation, more airflow rises from below the furniture over the table tops; however, the associated recirculation areas are smaller and mostly occur on top of the existing desks. While assessing the influence of manikin geometry on airflow is not the primary objective of this study, these results indicate that, in certain regions of the room, the geometric representation of the manikin geometry can have a greater impact on airflow than the geometry of furniture legs.

We have observed that block furniture in fLOD 1 tends to redirect airflow excessively, leading to greater inconsistencies than in fLOD 3. Planar surfaces without any thin structures in fLOD 2 overestimate airflow in the recirculation regions compared to furniture with thin structures. We have also seen that the differences in velocity magnitude between fLODs can double in value between displacement and mixing ventilation. These differences demonstrate how the block, surface, and linear furniture features affect airflow and how they interact with various ventilation regimes.

5.3.2 Temperature and passive scalar concentration

The differences between the fLODs in temperature and passive scalar concentration are mainly governed by variations in the velocity magnitude of the breathing jets, rather than by the background flow. The breathing jets act as the primary source of temperature and passive scalar concentration. Consequently, changes in jet velocity directly affect the rate at which heat and scalar are released, transported, and diluted in the near-field region. In contrast, the background

flow, especially with fLOD 1, has a comparatively weaker influence on the resulting temperature and scalar differences. We also observe larger differences in both passive scalar concentration and temperature values under displacement ventilation compared with mixing ventilation. Specifically, the maximum relative difference in passive scalar concentration is 19% under mixing ventilation, whereas it reaches 95% under displacement ventilation, almost five times as much. Similarly, the maximum temperature difference under mixing ventilation is 4.5 °C, compared with 15°C for displacement ventilation, three times higher than with mixing ventilation (see Figures 5.9, 5.10, 5.11, and 5.12, and see B.2 for the results for the head and block cases).

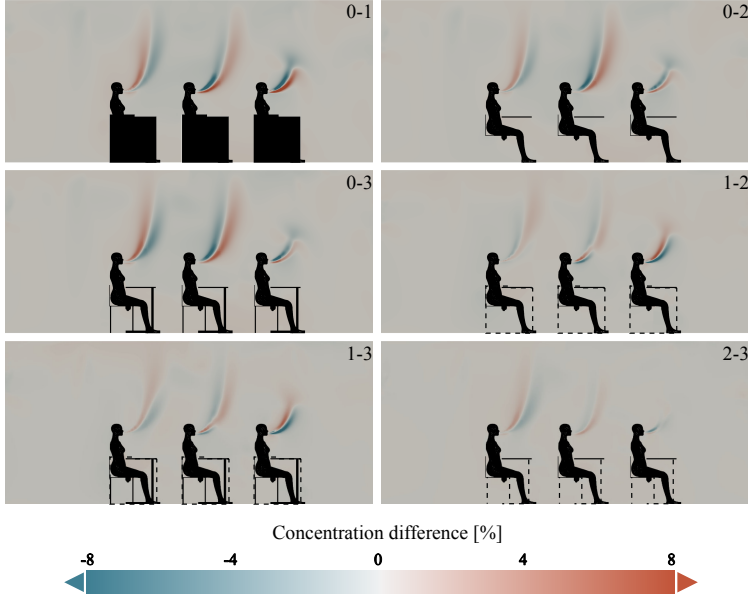


Figure 5.9: Concentration differences under mixing ventilation with the full body case - scale bar is shown at the 99th percentile for better contrast and text in the top corner is fLOD_x minus fLOD_y

These significant differences under displacement ventilation can be due to the dominant role of the breathing jet in determining local temperature and passive scalar concentration, combined with the stronger sensitivity of the breathing jet velocities to fLOD variations in displacement ventilation relative to mixing ventilation, as we previously saw in Section 5.3.1. Additionally, different airflow variables exhibit varying sensitivities to the ventilation regime, with velocity magnitude differences approaching a factor of 2 and passive scalar differences

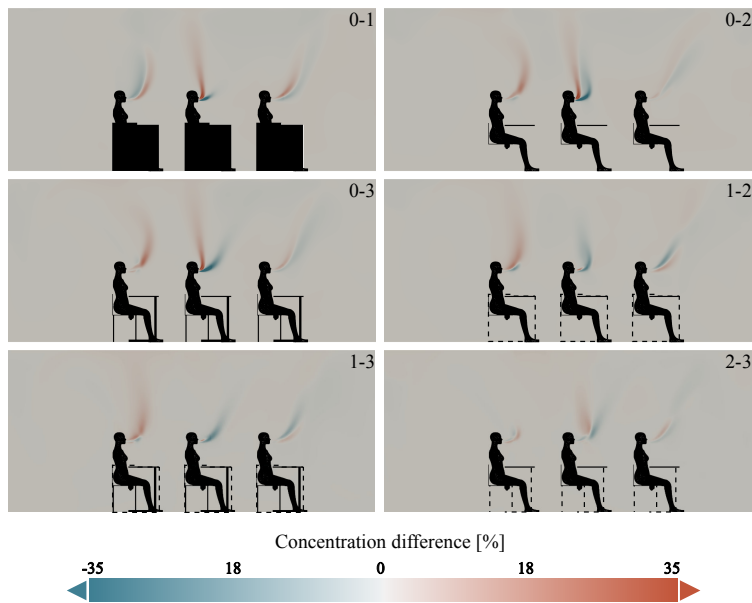


Figure 5.10: Concentration differences under displacement ventilation with the full body case - scale bar is shown at the 99th percentile for better contrast and text in the top corner is fLODx minus fLODy

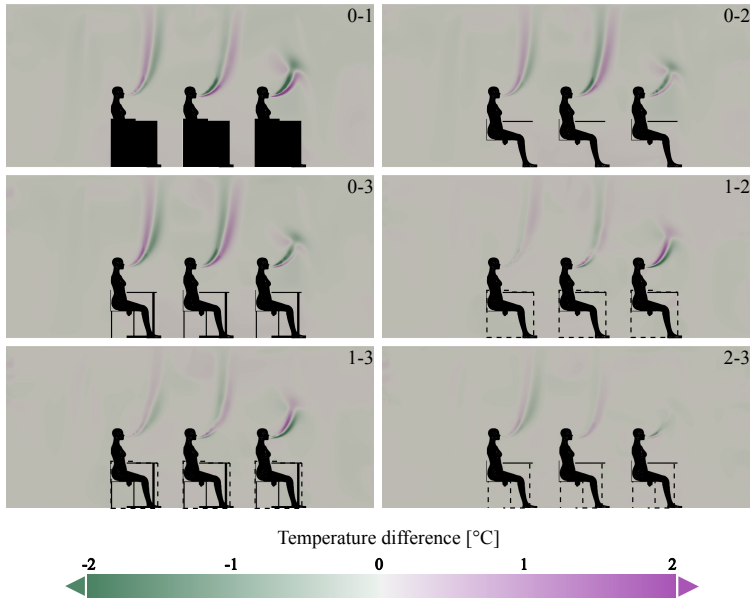


Figure 5.11: Temperature differences under mixing ventilation with the full body case - scale bar is shown at the 99th percentile for better contrast and text in the top corner is fLODx minus fLODy

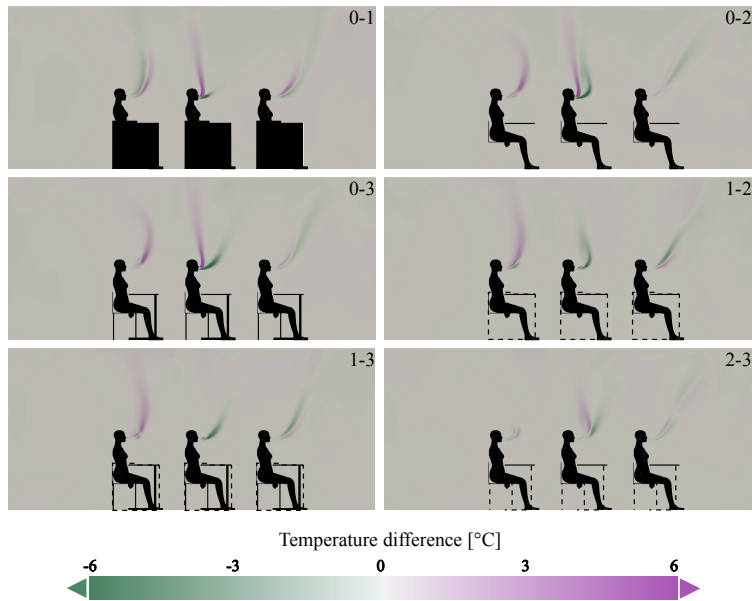


Figure 5.12: Temperature differences under displacement ventilation with the head only case - scale bar is shown at the 99th percentile for better contrast and text in the top corner is fLODx minus fLODy

increasing up to 5-fold, indicating that the appropriate choice of fLOD depends on the variable being studied and the ventilation regime.

5.3.3 Manikin level of detail

Since furniture typically modelled as blocks is used with manikins also modelled as blocks [Mottet, 2023; Ren et al., 2022] to maintain a level of geometric consistency, we also examine the impact of manikin representation by comparing a block manikin and a humanoid-shaped manikin with fLOD 1 furniture. We observe that a broader, stronger breathing jet develops with the block manikin (see Figure 5.13). The block manikins appear to act as larger obstacles than the humanoid manikins, allowing for an overprediction of the shape and strength of the breathing jet. This discrepancy between more detailed computational manikins and simpler ones aligns with previous studies on manikin geometry simplification [Topp et al., 2002, 2003; Yan et al., 2016].

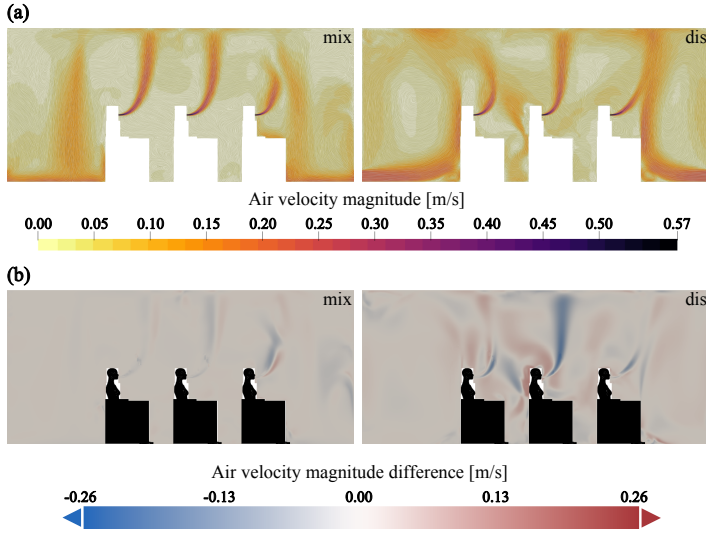


Figure 5.13: a) Air velocity magnitude under mixing (mix) and displacement (dis) ventilation with the block manikin case (b) Air velocity magnitude differences under mixing (mix) and displacement (dis) ventilation between the full body manikins and the block manikins for fLOD 1 - scale bar is shown at the 99th percentile for better contrast.

5.3.4 Limitations and future work

This study has several limitations that warrant further research. The numerical differences between simulation results using different fLODs presented in this study have not been validated against experimental measurements; however, the solver chosen for the simulations has already been validated against breathing jet experiments (see Chapter 4). Future work should include comparisons with experiments to assess the accuracy of the predicted airflow under controlled conditions.

Additionally, although this is the start of a definition for a generalised framework for level of detail in indoor airflow and ventilation simulations, further analysis is necessary across multiple cases and ventilation regimes to provide guidelines on how to represent inlets, outlets, manikins, and furniture at varying levels of geometric complexity, depending on the application and ventilation regime, aiming to strike a balance between computational cost and accuracy.

Another limitation of this study is the use of steady-state simulations. With 12 occupants in the room, breathing is transient and asynchronous, introducing time-varying flow that modifies the mean airflow from steady simulations. Future work should consider transient simulations incorporating asynchronous breathing to assess how unsteady respiratory flows interact with geometric complexity. However, the objective of this study was to isolate and assess the impact of geometric furniture representation on the simulated airflow, clearly showing the differences in fLODs.

Finally, the simulations in this study focus on one classroom environment with one set of furniture. Extending the analysis to other geometries and indoor settings, such as offices and hospitals, would allow the generality of the conclusions to be evaluated.

5.4 Conclusion

In this work, we propose a framework for defining fLODs, enabling a more systematic characterisation of the level of detail in indoor geometries, facilitating the study of indoor airflow and ventilation, and enabling comparisons across different numerical studies. Our results demonstrate that fLOD affects indoor airflow, with its impact on velocity, temperature, and passive scalar transport depending on the ventilation regime and the specific application. Different geometric features - block, surface, and linear - interact differently with the airflow, leading to variations in flow structures both in the breathing jet and the background flow. Highly simplified block furniture tends to redirect airflow excessively, leading to premature exhaust of breathing jets or an overestimation of jet development in recirculation regions. Additionally, furniture representations consisting solely of

planar surfaces overpredict airflow intensity in recirculation regions compared to furniture with linear thin structures. The resulting differences of representing the same furniture at different fLOD in the background flow can reach up to 100% of the ventilation inlet velocity, and differences in the breathing jet can reach up to 82% of the inlet velocity at the mouth. Furthermore, the ventilation regime, especially the positions of the inlet and outlet, can significantly amplify those differences, at least doubling velocity magnitude differences, tripling temperature differences, and more than quadrupling scalar concentration differences. These findings indicate that the choice of fLOD should be guided by the intended application, the variable of interest, and the ventilation regime under consideration. For example, studies interested in thermal comfort with mixing ventilation may use fLOD 1; whereas studies interested in aerosol dispersion with displacement ventilation may use fLOD 3.

6 Conclusions and Future Work

Ventilation plays an important role in maintaining the overall health and well-being of building occupants. Assessing ventilation performance experimentally and numerically helps inform the design of better indoor spaces that provide improved indoor air quality, which becomes of paramount importance during crises such as pandemics. However, current experimental and numerical approaches to study ventilation performance are time-consuming, manual, or computationally intensive. In this research, I have investigated various approaches to make studying ventilation more feasible, including developing a robot to automate indoor airflow measurements while avoiding disruption of the surrounding air by human operators, identifying the most suitable CFD solver for indoor ventilation simulations, and proposing a framework for the level of detail of furniture for CFD simulations.

6.1 Answer to the research subquestions

The main research question of this thesis is: *Can low-cost numerical and experimental methods accurately and robustly assess indoor ventilation performance [at different stages of a building's life cycle]?* I address the main research question by subdividing it into four sub-questions. In this section, I answer these four research questions and connect them to answer the main research question in the following section.

Q1: How do current experimental and numerical practices and assumptions impact indoor and respiratory airflow predictions? (see Chapter 2)

Indoor and respiratory airflow predictions depend on the experimental and numerical practices used to investigate them. In indoor environments, airflow patterns are influenced by factors such as mechanical ventilation jets and exhalation jets from the mouth. These jets, in turn, are influenced by several factors, including boundary conditions, thermal effects, and room geometry, which contribute to deviations from the theoretical jet development and decay. Both experimental and numerical approaches rely on simplifying assumptions to represent these complex processes, which can affect the resulting airflow predictions.

In experimental studies, low-cost methods often rely on point-wise measurements and simplified representations of exhalation flows. These measurements are typically taken either along the jet centreline or in the surrounding airflow to understand the jet's impact and interaction with the room airflow. These measurements show that, in practice, breathing and ventilation jets can differ from theoretical jet behaviour due to the shape of the inlet opening, the presence of walls, and buoyancy effects in indoor spaces.

In parallel, numerical simulations, particularly RANS CFD simulations, also show similar jet behaviour, as validated by experimental measurements. However, different modelling assumptions used in the literature for comparable indoor flows, such as turbulence models, thermal assumptions, and boundary conditions, can lead to variations in predicted airflow patterns. Consequently, commonly used low-cost approaches aim to balance predictive accuracy with the computational cost required to obtain the results.

Q2: How can point-wise indoor measurements be automated while reducing interference with the surrounding airflow during measurements? (see Chapter 3)

To address the time and labour cost of manual measurements of airflow characteristics, I designed and built an autonomous line-following robot, Milou. Milou follows a line and stops at predefined sampling points to measure the magnitude of airflow velocity and temperature. During the design of Milou, I used low-cost materials to reduce the robot's overall cost (1,000 euros total cost). I also used low-heat-emitting electronic devices and minimised their presence on board as much as possible by remotely connecting to the needed computers. Additionally,

6.1 Answer to the research subquestions

I designed Milou with a slender structure to minimise airflow disturbance during movement.

To test Milou's effect on measurements, I deployed it in a test chamber and evaluated its repositioning accuracy, its impact on the chamber's airflow temperature, and the repeatability of the airflow velocity magnitude measurements. The results show that Milou consistently stops at designated sampling points with millimetre accuracy for IAQ studies. Additionally, its electrical components do not affect temperature readings, while airflow velocity remains consistent across different flow conditions. Milou demonstrates that airflow measurements can be automated, thereby reducing both the time invested in manual labour and the interference from human operators in the measured airflow.

Q3: Which CFD solver has the best cost-to-applicability compromise to support ventilation-based design optimisation? (see Chapter 4)

To support performance-based ventilation-based design, assuming steady, weakly compressible flow yields accurate yet efficient numerical results that capture ventilation airflow and breathing jet decay. Based on previous ventilation studies, I have identified three physics assumptions for airflow modelling: isothermal and incompressible flow, thermal and incompressible flow, and thermal and weakly compressible flow. I have compared three solvers that correspond to those three assumptions to support the simplified inclusion of breathing individuals in ventilation-based design assessments.

To validate the modelled breathing jet for the isothermal flow, I acquired velocity magnitude data along the breathing jet of a manikin head in a controlled test chamber. For the thermal flow, I validated the CFD results against the free-jet decay theory and literature data. Based on the validated results and comparisons among the three solvers, the thermal compressible flow solver most accurately represents the breathing jet with background ventilation, closely matching the linear momentum decay in the fully developed region of the breathing jet, with a -1.08 slope, compared to the theoretical -1 slope and the -0.81 slope for thermal incompressible flow.

Q4: What is a suitable fLOD definition for indoor ventilation simulations, and what is the impact of those different levels of detail? (see Chapter 5)

Furniture is often inconsistently modelled in the literature, sometimes as over-simplified blocks and sometimes without its thin structure. The appropriate choice of furniture's geometric level of detail (fLOD) can reduce computational time; however, there is currently no systematic consensus on fLOD's impact or on how that choice affects airflow results. I addressed this gap by defining a framework for furniture level of detail (fLOD) based on three geometric features: block, planar, and linear, and systematically compared the results across the different fLODs in the framework.

6 Conclusions and Future Work

The results show that the chosen geometrical features are relevant. Block furniture significantly interferes with the airflow pattern and, consequently, the breathing jets. Additionally, linear features, such as furniture supports, can create sufficient airflow blockage when numerous tables and chairs are in the room. Finally, the airflow of different ventilation regimes is affected differently by different fLODs. Depending on the application and ventilation regime, this can help building engineers make more informed decisions about the needed furniture geometry in their simulations.

6.2 Answer to the main research question and overall discussion

Can low-cost numerical and experimental methods accurately and robustly assess indoor ventilation performance [at different stages of a building's life cycle]?

Low-cost experimental and numerical methods offer a pragmatic approach to integrate indoor airflow assessment throughout the building life cycle. At the early performance-based design stage, simplified models with appropriate assumptions strike a balance between computational cost and accuracy. Choosing appropriate assumptions for the simulations, in this case weakly compressible thermal flow, increases the accuracy of the breathing jet modelling without incurring additional computational cost compared to incompressible thermal flow (see Chapter 4). Additionally, with appropriate simplified geometric models, the computational domain of simulations can be reduced, reducing computational cost (see Chapter 5). While the computational cost of RANS simulations remains a limiting factor for iterative design approaches, this thesis demonstrates the potential of appropriately making assumptions for modelling indoor airflow. At the occupied built stage of the building, low-cost monitoring using a mobile robot makes post-occupancy evaluation more feasible and accurate (see Chapter 3). Point-wise measurements can be easily automated, reducing labour costs and operators' mistakes during measurement campaigns. Although more work is needed to improve the implementation of robots for assessing indoor airflow, this thesis shows how the robotics field can significantly enhance measurement campaigns in buildings.

Making these methods more accessible bridges the gap between the theoretical performance of a design solution and the optimal practical solution for a given indoor space. This enhanced accessibility allows for healthier and more resilient buildings, reduced airborne transmission risks indoors, and a better energy-health balance. Ultimately, the value of low-cost approaches lies not only in affordability, but in enabling widespread, iterative, and data-informed improvement of buildings where people live, work, and, inevitably, breathe.

6.3 Limitations and Future Work

This thesis has several limitations that should be acknowledged. While each chapter contains specific, detailed limitations, this section focuses on the broader limitations of this thesis. First, Milou should achieve full operational autonomy. While Milou's current design demonstrates reliable acquisition and mobility, the early preparation stages still require manual effort, such as defining the line and sampling points for Milou to follow. The next version of Milou should integrate navigation in dynamic and unmapped environments, enabling it to operate without human intervention in complex indoor environments. In addition, Milou should be deployed in a larger, more realistic environment to assess its indoor air monitoring capabilities under practical conditions.

Second, the indoor environmental indicators included in this study are limited to velocity magnitude, temperature and passive scalar dispersion. This allowed me to focus on a subset of variables, reducing the complexity of my models. However, important indicators such as relative humidity and aerosol dispersion are not included in this study, which hinders a holistic indoor air assessment.

Third, while this work contributes towards a furniture level of detail framework, a fully holistic indoor level of detail framework is still required. The indoor level of detail framework should standardise the modelling of inlets and outlets, manikins, and furniture for indoor ventilation simulations. Additionally, the holistic approach would advise on how to collect data on the geometry of the indoor space, including laser-scanned, detailed models of the space and furniture to support different types of simulations.

Moreover, to limit the scope of this study, I focused on mechanical ventilation in classroom and laboratory settings. These environments do not represent the diversity of building/room types, ventilation regimes, occupancy patterns, and usage scenarios found in practice. Expanding the application to a wider variety of spaces, such as offices and hospitals, would strengthen the findings of this study.

Future research should also investigate additional numerical and data-driven methods to reduce the computational cost of indoor CFD modelling while maintaining good accuracy. Machine learning and deep learning approaches should be explored to develop surrogate models or physics-based frameworks that rapidly predict indoor airflow and related variables. Such methods could significantly shorten simulation times, making CFD-based analyses more feasible for iterative design and early decision support in the built indoor environment.

Finally, I did not examine the integration of the proposed modelling approaches from Chapters 4 and 5 into practical design workflows, including parametric and performance-based design approaches. Testing the methods developed in this study within iterative design contexts would provide valuable insights into their

6 Conclusions and Future Work

usability, computational feasibility, and decision-making value in a more applied setting.

A Milou: supporting material

A.1 Open-source deliverables and list of main electrical components

To support reproducibility and community use, we provide a set of open-source resources and technical details related to Milou.

Table A.1 summarises the available materials, including control code, mechanical design files and documentation. All files are accessible via the following public repository: <https://doi.org/10.5281/zenodo.15082684>.

Table A.1: Summary of open-source deliverables

Deliverable	Description
Control code	Line following navigation and control algorithms
CAD Files	3D models for 3D printed custom components, 2D drawings for plexiglass laser cutting
Datasets	VR, HOBOs and HSAs logs
Documentation	Setup instructions

Table A.2 provides technical details about the main electrical components on Milou.

Table A.2: List of main electrical components on Milou

Component	Function
Arduino Nano Every microcontroller	Processing of IR sensor readings and motor control
Raspberry Pi Zero W	Wi-Fi access point for data relay to remote computer
MG996R servo motor 1.3 Nm torque (2x)	Continuous rotation of driving wheels
TCRT5000 Infrared Sensor Array	Line detection
Green Cell 12.4V LiFePO4 Battery (38Ah)	Power supply for all electrical components
QSKJ XL4016 step-down converter to 9V (200W)	Power conversion for Dantec mainframe
MINI 560 PRO step-down converter to 5V (5A)	Power conversion for Arduino and Raspberry Pi
MINI 560 PRO step-down converter to 5V (5A)	Power conversion for servo motors

A.2 Computational Fluid Dynamics (CFD) representation of the airflow in the test chamber

The following CFD simulations serve as supporting material for the measurement campaign described in this paper. The mesh has 9 million cells, with a background cell size of 2.5 cm and additional refinement near the walls. We use OpenFOAM ESI to run simpleFoam with second-order discretisation schemes and show the airflow patterns in the chamber. The aim of the results is solely to support our argumentation on the airflow pattern, and they in no way represent a numerical validation of the measurements. Figure A.1 shows the airflow pattern in the chamber from the ventilation system. Figure A.2 shows (a) 1.1 m (height of probe 1), (b) 1.3 m (height of probe 2), (c) 1.7 m (height of probe 3).

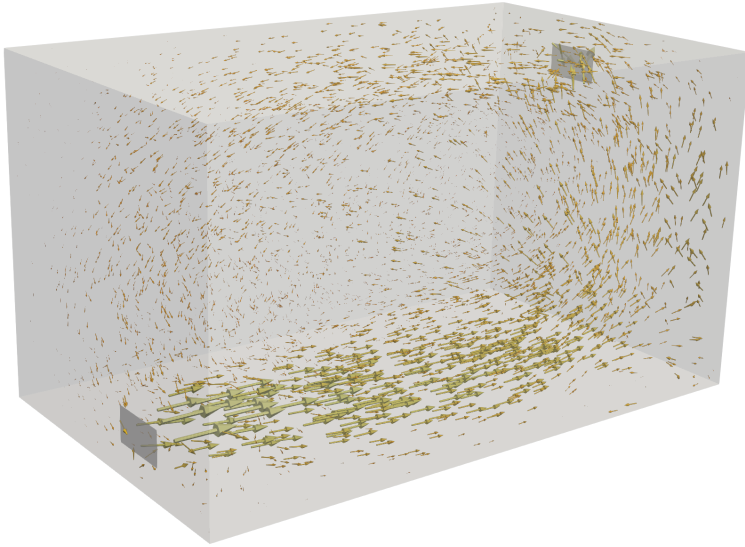


Figure A.1: Vector representation of the airflow patterns in the chamber from the inlet of the ventilation system. The size of the arrow is proportional to the magnitude of the airflow velocity vector.

A.2 Computational Fluid Dynamics (CFD) representation of the airflow in the test chamber

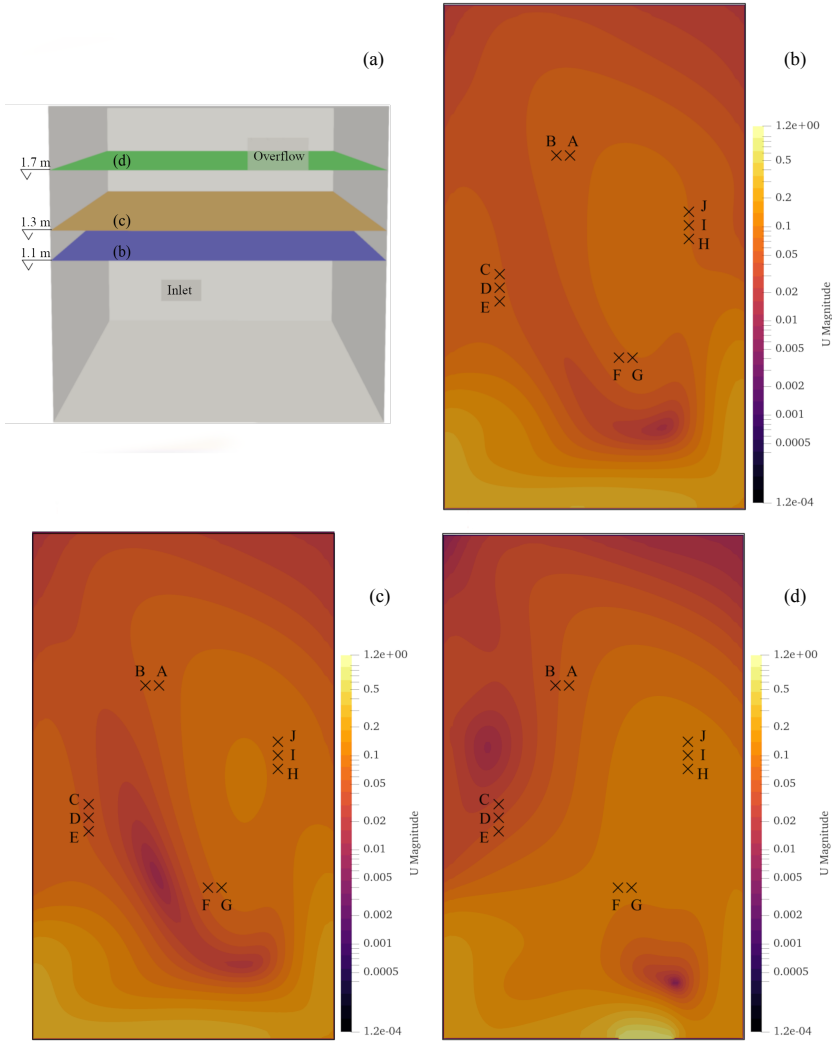


Figure A.2: (a) 3D view of the three planes in the room where the hot-sphere anemometers measure. Plane sections at the height of (b) 1.1 m (height of probe 1), (c) 1.3 m (height of probe 2), (d) 1.7 m (height of probe 3). The points are the sampling points presented in this study.

B The devil is in the details: supporting material

B.1 Furniture simplification proof-of-concept implementation

This appendix describes the proof-of-concept implementation for generating fLOD 1, 2, and 3, as implemented in [Hobeika et al. \[2026b\]](#). For fLOD 1, the oriented bounding box of the furniture geometry is computed using a built-in function from the Python library ‘trimesh’.

For fLOD 2 and 3, furniture geometry is simplified by identifying and filtering finer parts from polygonal meshes using a diameter threshold implemented using a test circle. Furniture meshes are first voxelised based on the smallest test circle diameter and then skeletonised using the distance transform computed at each voxel. The resulting skeleton provides an initial decomposition of the furniture into candidate parts using nearest-neighbour mapping. However, this process incorrectly labels certain voxels as distinct parts. To address this issue, an additional step ensures that those voxels are assigned to the correct furniture part. This step assumes that coplanar faces belong to the same furniture part and that they are located within the part’s oriented bounding box. Once parts are identified, each part is projected onto three orthogonal planes, using its oriented bounding box. For each projection, a circle fitting test is performed using a circle diameter δ . If the circle fits at least one of the projections, the part is retained in the final furniture geometry. Otherwise, the part is discarded.

Finally, all retained parts are checked for watertightness. Non-watertight parts are repaired by detecting holes in the mesh. Boundary edges, defined as edges incident to a single triangular face, are grouped into closed loops that represent holes in the mesh. For each closed loop, duplicate vertices are removed, and a best-fit plane is estimated using least-squares fitting. The loop vertices are projected into this plane to form a 2D polygon, which is triangulated using constrained Delaunay triangulation while preserving the boundary edges. The resulting triangles are then back-projected into 3D space and added to the part’s mesh. This step makes each part geometrically consistent and watertight.

This code has been verified only for the furniture geometry used in this study and should be further tested to assess its performance with other furniture shapes.

B.2 Temperature and passive scalar concentration

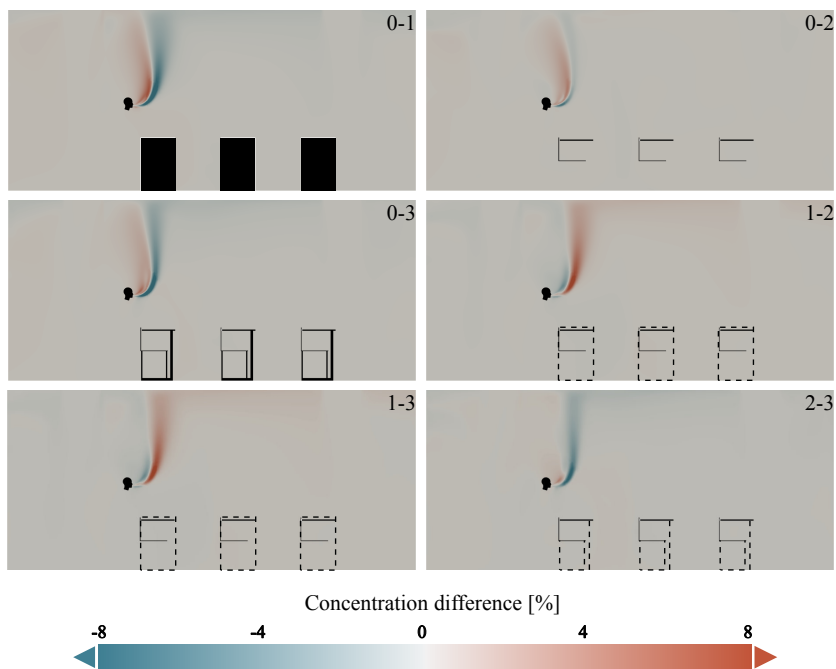


Figure B.1: Concentration differences under mixing ventilation with the head only case - scale bar is shown at the 99th percentile for better contrast and text in the top corner is fLODx minus fLODy

B.2 Temperature and passive scalar concentration

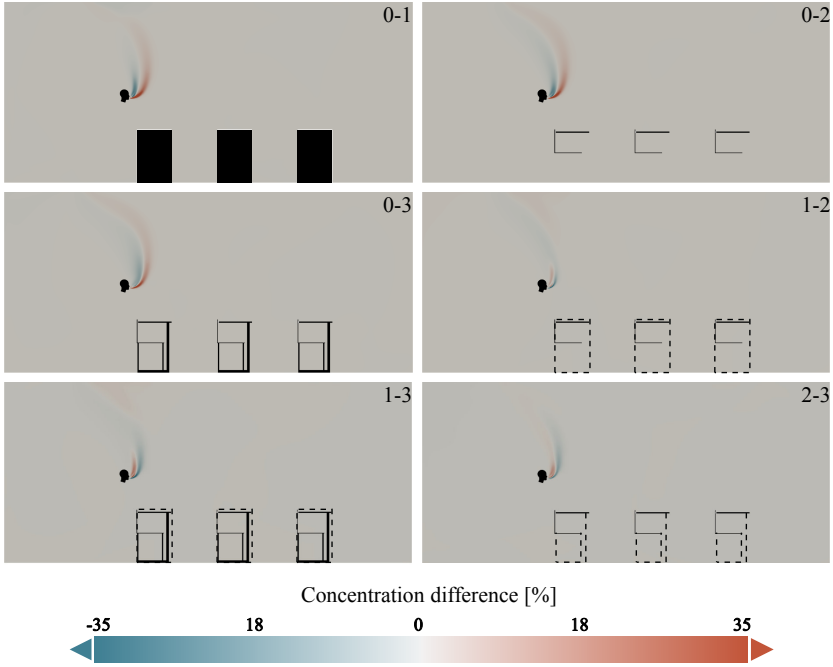


Figure B.2: Concentration differences under displacement ventilation with the head only case - scale bar is shown at the 99th percentile for better contrast and text in the top corner is fLODx minus fLODy

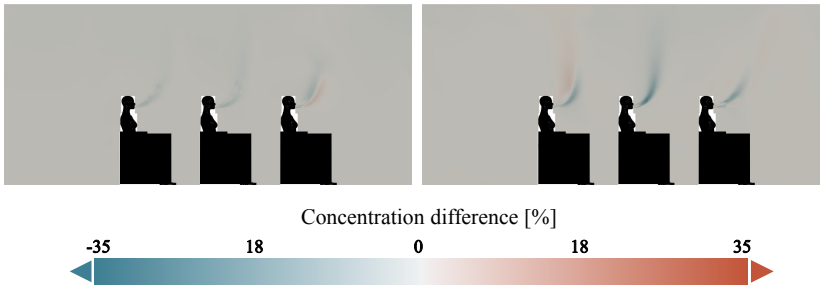


Figure B.3: Concentration differences under mixing and displacement ventilation between the full body manikins with the block manikins for fLOD 1 - scale bar is shown at the 99th percentile for better contrast

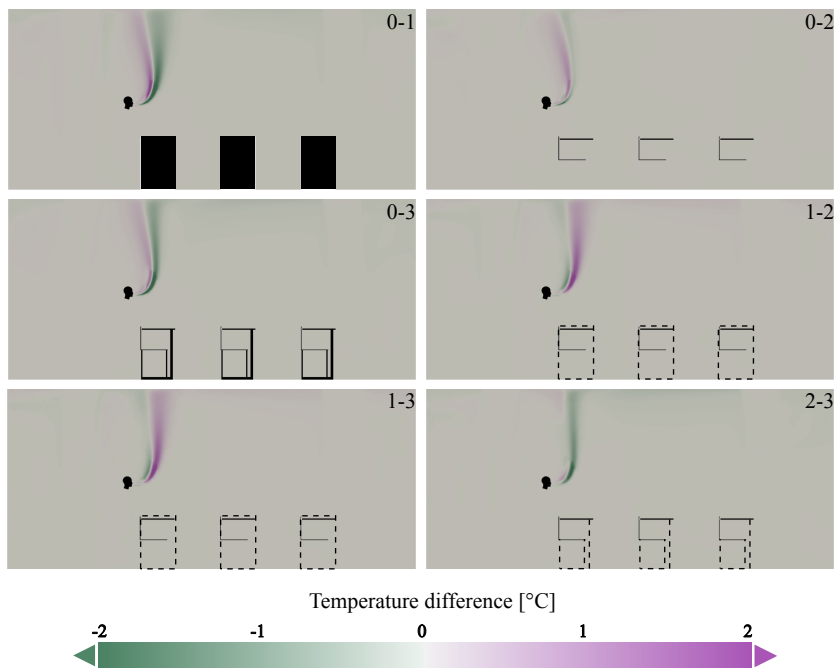


Figure B.4: Temperature differences under mixing ventilation with the head only case - scale bar is shown at the 99th percentile for better contrast and text in the top corner is fLODx minus fLODy

B.2 Temperature and passive scalar concentration

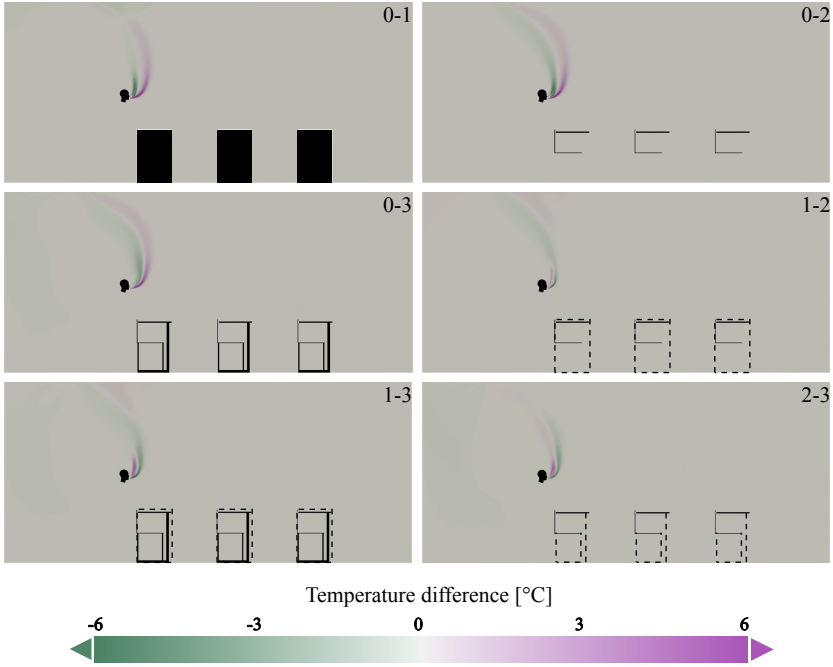


Figure B.5: Temperature differences under displacement ventilation with the head only case - scale bar is shown at the 99th percentile for better contrast and text in the top corner is fLODx minus fLODy

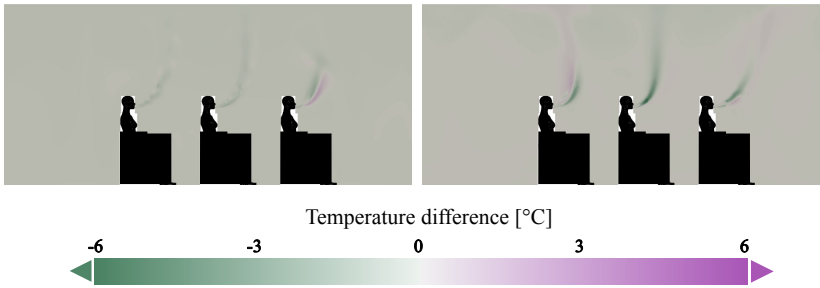


Figure B.6: Temperature differences under mixing and displacement ventilation between the full body manikins with the block manikins for fLOD 1 - scale bar is shown at the 99th percentile for better contrast

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Summary

This thesis explores and evaluates low-cost, efficient assessment methods for predicting indoor airflow and ventilation to support more accessible, performance-based building design. It addresses two aspects of indoor airflow assessment: (1) automating point-wise measurements, and (2) reducing the computational cost of RANS CFD simulations by leveraging different assumptions and geometry simplifications.

The first part of this thesis explores automating point-wise measurements of air velocity magnitude and temperature to reduce their operational cost. To that end, I designed and validated a line-following robot that stops at marked sampling points and conducts measurements. This line-following robot performs measurements with negligible impact on measurement quality and is four times faster than a human operator.

The second part focuses on identifying the most suitable numerical assumptions that balance the accuracy of the results and the computational cost for modelling breathing jets with background airflow ventilation. I conducted a validation study comparing measurements from the robot and the literature, with results from three computational fluid dynamics solvers that employ three different assumptions about the flow: incompressible isothermal, incompressible thermal, and compressible thermal. Compressible thermal flows model the breathing jet most accurately without increasing computational cost.

Therefore, using the compressible thermal solver, I finally propose a framework for indoor furniture's geometric level of detail (fLOD) to systematically study the effects of modelling detail on airflow prediction and to reduce the computational cost of mesh generation for CFD simulations. Representing the same furniture at different fLOD can result in differences in airflow velocity up to 100% of the ventilation inlet velocity. Additionally, the ventilation regime, especially the positions of the inlet and outlet, can significantly amplify those differences, at least doubling velocity magnitude differences, tripling temperature differences, and more than quadrupling scalar concentration differences for the same furniture across different fLODs. The choice of fLOD should be guided by the intended application, the variable of interest, and the ventilation regime under consideration.

Summary

In conclusion, this thesis has developed low-cost assessment methods for indoor airflow to enable ventilation-based performance-based building design. It has shown that low cost is not necessarily tied to reduced accuracy. This thesis is a first step toward more feasible, iterative design processes that include characterising airflow and ventilation to improve indoor air quality.

Samenvatting

Dit proefschrift onderzoekt en evalueert goedkope, efficiënte beoordelingsmethoden voor het voorspellen van binnenluchtstroming en ventilatie, ter ondersteuning van een toegankelijker, prestatiegericht gebouwwontwerp. Het behandelt twee aspecten: (1) het automatiseren van puntsgewijze metingen en (2) het verlagen van de rekenkosten van RANS numerieke stromingsleer (CFD) simulaties door gebruik te maken van verschillende aannames en geometrische vereenvoudigingen.

Het eerste deel van dit proefschrift onderzoekt het automatiseren van puntsgewijze metingen van luchtsnelheid en temperatuur om de operationele kosten te verlagen. Hiertoe hebben we een lijn volg robot ontworpen en gevalideerd die stopt bij gemarkeerde meetpunten en daar metingen uitvoert. Deze lijn volg robot voert metingen uit met een verwaarloosbare impact op de kwaliteit van de metingen en is vier keer sneller dan een menselijke operator.

Het tweede deel richt zich op het vinden van de meest geschikte numerieke aannames die een balans bieden tussen de nauwkeurigheid van de resultaten en de rekenkosten voor het modelleren van ademhalingsjets met achtergrondventilatie. Ik heb een validatiestudie uitgevoerd waarbij metingen van de robot en de literatuur werden vergeleken met resultaten van drie computationele vloeistofdynamica-solvers die drie verschillende aannames over de stroming hanteren: onsamendrukbare isotherme, onsamendrukbare thermische en samendrukbare thermische stromingen. Samendrukbare thermische stromingen modelleren de ademhalingsjet het meest nauwkeurig zonder de rekenkosten te verhogen.

Vervolgens, en gebruikmakend van de samendrukbare thermische solver, stel ik een raamwerk voor om het geometrische detailniveau van binnenmeubilair (fLOD) systematisch te bestuderen en de effecten van modelleringsdetail op luchtstroomvoorspelling te verlagen, evenals de rekenkosten voor meshgeneratie bij CFD-simulaties. Het weergeven van hetzelfde meubilair op verschillende fLOD's kan leiden tot verschillen in luchtstroomsnelheid tot wel 100% van de inlaatsnelheid van de ventilatie. Bovendien kan het ventilatieregime, met name de posities van de inlaat en uitlaat, deze verschillen verder versterken, waardoor de snelheidsverschillen minstens verdubbelen, de temperatuurverschillen verdrievoudigen en de scalaire concentratieverschillen voor hetzelfde meubilair bij verschillende fLOD's meer dan verviervoudigen. De keuze van de fLOD moet

Samenvatting

worden bepaald door de beoogde toepassing, de variabele van belang en het te overwegen ventilatieregime.

Concluderend ontwikkelt dit proefschrift goedkope beoordelingsmethoden voor binnenluchtstroming, waarmee ventilatiegebaseerd, prestatiegericht gebouwo ontwerp mogelijk wordt. Het toont aan dat lage kosten niet noodzakelijkerwijs gepaard gaan met een lagere nauwkeurigheid. Dit proefschrift is een eerste stap naar meer haalbare, iteratieve ontwerpprocessen die het karakteriseren van luchtstroming en ventilatie omvatten om de binnenluchtkwaliteit te verbeteren.

Résumé

Cette thèse explore et évalue des méthodes d'évaluation à faible coût et efficaces pour prédire les flux d'air intérieurs et de ventilation, afin de favoriser une conception de bâtiments plus accessible et axée sur la performance. Elle aborde deux aspects de l'évaluation des flux d'air intérieurs : (1) l'automatisation des mesures sur site ponctuelles et (2) la réduction du coût de calcul des simulations de dynamique de fluide numérique (CFD) RANS grâce à l'utilisation de différentes hypothèses et de simplifications géométriques.

La première partie de cette thèse porte sur l'automatisation des mesures ponctuelles de la vitesse et de la température de l'air afin d'en réduire les coûts opérationnels. À cette fin, j'ai conçu et validé un robot suiveur de ligne s'arrêtant aux points d'échantillonnage marqués et effectuant les mesures. Ce robot réalise ces dernières avec un impact négligeable sur leur qualité et est quatre fois plus rapide qu'un opérateur humain.

La seconde partie a pour but d'identifier les hypothèses numériques présentant le meilleur équilibre entre la précision des résultats et le coût de calcul dans la modélisation des jets respiratoires avec ventilation. J'ai mené une étude de validation comparant les mesures du robot et les données de la littérature, à l'aide de trois solveurs de dynamique des fluides numérique utilisant trois hypothèses concernant le flux d'air : incompressible isotherme, incompressible thermique et compressible thermique. Les flux thermiques compressibles modélisent le jet respiratoire avec la plus grande précision, sans augmenter le coût de calcul.

En utilisant un solveur thermique compressible, je propose finalement un modèle pour le niveau de détail géométrique du mobilier d'intérieur (fLOD) afin d'étudier systématiquement les effets du niveau de détail de modélisation sur la prédiction des flux d'air et de réduire le coût de calcul lié à la génération du maillage pour les simulations CFD. La représentation d'un même meuble à différents fLOD peut entraîner des différences de vitesse de l'air allant jusqu'à 100% de la vitesse d'entrée de ventilation. De plus, le régime de ventilation, en particulier la position des entrées et des sorties, peut amplifier considérablement ces différences, en doublant au moins les écarts de vitesse, en triplant les écarts de température et en multipliant par plus de quatre les écarts de concentration scalaire pour un même meuble à différents fLOD. Le choix du fLOD doit être guidé par l'application prévue, la variable d'intérêt et le régime de ventilation considéré.

Résumé

En conclusion, dans cette thèse, j'ai développé des méthodes d'évaluation à faible coût des flux d'air intérieurs, permettant une conception de bâtiments axée sur la performance et la ventilation. J'ai démontré que le faible coût n'est pas nécessairement synonyme d'une moindre précision. Cette thèse constitue une première étape vers des processus de conception itératifs plus réalisables, intégrant la caractérisation des flux d'air et de la ventilation afin d'améliorer la qualité de l'air intérieur.

ملخص

تهدف هذه الأطروحة الى الكشف عن أساليب منخفضة التكلفة وفعالة لدراسة تدفق الهواء الداخلي والتهوية في الأقسام داخل المباني، دعماً لأخذ هذه الأساليب بعين الاعتبار في تصميم الابنية، وجعل دراستها أكثر سهولة في التطبيق. ستطرق هذه الأطروحة الى جانبين من تقييم تدفق الهواء الداخلي: (1) النماذج القياسية الموضوعية بشكل أوتوماتيكي، (2) تقليل التكلفة الحاسوبية لمحاكاة ديناميكيات الموائع (السوائل والغازات) الحاسوبية (CFD) باستخدام نموذج RANS من خلال الاستفادة من افتراضات مختلفة وتبسيطات هندسية.

يركّز الجزء الأول من هذه الأطروحة على النماذج القياسية الموضوعية بشكل أوتوماتيكي لمقدار سرعة الهواء ودرجة حرارته بهدف تقليل التكلفة التشغيلية. ولتحقيق ذلك، قمت بتصميم رجل آلي يتبع خطاً محدداً، حيث يتوقف عند نقاط معلّمة ويجري القياسات المطلوبة. وقد قمت بالتحقق من صحة قياسات هذا الرجل الآلي، فهو يؤدي مهامه مع تأثير ضئيل جداً على جودة القياسات أسرع بأربع مرات من مشغل بشري. أما الجزء الثاني، فيركّز على تحديد الافتراضات العددية الملائمة لتحقيق توازن بين دقة النتائج والتكلفة الحاسوبية عند احتساب التنفس البشري النموذجي مع وجود تهوئة. وقد أجريت دراسة قارنت بين القياسات التي تمّ الحصول عليها بمساعدة الرجل الآلي ودراسة أخرى، مع نتائج ثلاث محلات لديناميكيات الموائع الحاسوبية تعتمد على ثلاث افتراضات مختلفة لتدفق الهواء: (1) غير قابل للانضغاط ومتساوي الحرارة، (2) غير قابل للانضغاط وحار، (3) قابل للانضغاط وحار. وقد تبين أن النماذج الحرارية القابلة للانضغاط تمثل التنفس البشري بدقة أعلى، دون زيادة في التكلفة الحاسوبية.

وبناءً على ذلك، وباستخدام المحلل الحراري القابل للانضغاط، أقترح في الختام أطراً لتحديد مستوى التفاصيل الجيومترية للأثاث الداخلي (fLOD)، وذلك لدراسة تأثير مستوى التصميم بشكل منهجي على دراسة تدفق الهواء، ولتقليل التكلفة الحاسوبية لإنشاء الشبكات لديناميكيات الموائع الحاسوبية. وقد يؤدي تمثيل نفس الأثاث بمستويات مختلفة من التفاصيل الجيومترية الى اختلافات في سرعة تدفق الهواء تصل الى 100% من السرعة عند مدخل التهوئة. بالإضافة الى ذلك، يمكن لنوع التهوئة، وخاصة مواقع فتحات الدخول والخروج، أن يضاعف هذه الاختلافات بشكل كبير، بحيث تضاعف فروقات السرعة على الأقل، وتزداد فروقات درجات الحرارة الى ثلاثة أضعاف، وتتجاوز فروقات تركيز المواد أربعة أضعاف نفس الأثاث عبر مستويات مختلفة من التفاصيل. لذلك ينبغي اختيار مستوى التفاصيل الجيومترية بناءً على التطبيق المقصود، العامل المتغير الأساسي ونمط التهوئة قيد الدراسة.

وفي الختام، طوّرت هذه الأطروحة أساليب تقييم منخفضة التكلفة لتدفق الهواء الداخلي، بهدف تمكين تصميم المباني القائم على الأداء المعتمد على التهوئة. وقد أظهرت أنّ انخفاض التكلفة لا يعني بالضرورة انخفاض الدقة. وتمثل هذه الأطروحة خطوة أولى نحو عمليات تصميم قابلة للتطبيق والتكرار، تتضمن توصيف تدفق الهواء والتهوئة لتحسين جودة الهواء الداخلي.

Curriculum Vitae

From 2013 to 2019, Nadine Hobeika studied at the Université Saint-Esprit Kaslik, Lebanon. There, she received her Bachelor's and Master's degrees in Architecture. After completing her Architecture program in 2019, she moved to the Netherlands to pursue a Master's in Geomatics at Delft University of Technology (TU Delft). In July 2021, she received her Geomatics Master's degree with her MSc thesis titled *CFD, sensitivity analysis and optimisation to promote the formation of dunes*. From 2021 to 2026, Nadine conducted her PhD research on *Improving indoor airflow assessment through low-cost experimental and numerical methods*, funded by an interdisciplinary PhD grant from the Faculty of Architecture and the Built Environment at TU Delft and supervised by Clara García-Sánchez and Jantien Stoter. In 2025, Nadine was hired by Arup, Dublin, as a microclimate and wind specialist.

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